TRB

TRANSPORTATION RESEARCH RECORD

Journal of the Transportation Research Board, No. 2162

Freight Systems

Intermodal Transportation, Hazardous Materials, and International Trade

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Freight Systems

Intermodal Transportation, Hazardous Materials, and International Trade

A Peer-Reviewed Publication

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Foreword

The 2010 series of the *Transportation Research Record: Journal of the Transportation Research Board* consists of approximately 900 papers selected from 3,700 submissions after rigorous peer review. The peer review for each paper published in this volume was coordinated by the committee acknowledged at the end of the text; members of the reviewing committees for the papers in this volume are listed on page ii.

Additional information about the *Transportation Research Record: Journal of the Transportation Research Board* series and the peer review process appears on the inside back cover. TRB appreciates the interest shown by authors in offering their papers, and the Board looks forward to future submissions.

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Measurement Conversion Factors

To convert from the unit in the first column to the unit in the second column, multiply by the factor in the third column.

Customary Unit	*SI Unit*	*Factor*
Length		
inches	millimeters	25.4
inches	centimeters	2.54
feet	meters	0.305
yards	meters	0.914
miles	kilometers	1.61
Area		
square inches	square millimeters	645.1
square feet	square meters	0.093
square yards	square meters	0.836
acres	hectares	0.405
square miles	square kilometers	2.59
Volume		
gallons	liters	3.785
cubic feet	cubic meters	0.028
cubic yards	cubic meters	0.765
Mass		
ounces	grams	28.35
pounds	kilograms	0.454
short tons	megagrams	0.907
Illumination		
footcandles	lux	10.76
footlamberts	candelas per square meter	3.426
Force and Pressure or Stress		
poundforce	newtons	4.45
poundforce per square inch	kilopascals	6.89

Temperature

To convert Fahrenheit temperature (°F) to Celsius temperature (°C), use the following formula:
°C = (°F – 32)/1.8

SI Unit	*Customary Unit*	*Factor*
Length		
millimeters	inches	0.039
centimeters	inches	0.394
meters	feet	3.281
meters	yards	1.094
kilometers	miles	0.621
Area		
square millimeters	square inches	0.00155
square meters	square feet	10.764
square meters	square yards	1.196
hectares	acres	2.471
square kilometers	square miles	0.386
Volume		
liters	gallons	0.264
cubic meters	cubic feet	35.314
cubic meters	cubic yards	1.308
Mass		
grams	ounces	0.035
kilograms	pounds	2.205
megagrams	short tons	1.102
Illumination		
lux	footcandles	0.093
candelas per square meter	footlamberts	0.292
Force and Pressure or Stress		
newtons	poundforce	0.225
kilopascals	poundforce per square inch	0.145

Temperature

To convert Celsius temperature (°C) to Fahrenheit temperature (°F), use the following formula:
°F = (°C × 1.8) + 32

Abbreviations Used Without Definitions

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials (known by abbreviation only)
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SHRP	Strategic Highway Research Program
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board

Analysis of Stacking Priority Rules to Improve Drayage Operations Using Existing and Emerging Technologies

Nathan Huynh and John Zumerchik

Of the many emerging technologies being developed to expedite the flow of cargo through intermodal facilities, automated transfer management systems (ATMSs) have the potential to improve trucks' in-terminal dwell times significantly while the trucks are performing outbound or inbound moves. This paper presents a framework for integrating existing technologies (e.g., intelligent transportation systems, e-business systems) and emerging technologies (e.g., ATMSs) and using this framework to shorten the time for a drayage truck to pick up an import container. Shortening this time is of critical importance in reducing engine idling time and stop-and-go lugging time. Reduced truck idling translates directly into reduced diesel emissions, including emission of fine particulate matter, nitrogen oxides, and greenhouse gases. This paper specifically investigates the effect of priority rules for stacking containers into the ATMS to improve port drayage operations. The analysis of priority rules is made on the basis of a computer simulation model developed for this study, and the analysis of emissions reduction is based on the U.S. Environmental Protection Agency's SmartWay DrayFLEET model. The obtained results confirm the hypothesis that the earliest arrival time priority rule yields better drayage performance than the closest appointment time priority rule.

A critical research issue raised by the speakers and participants at TRB's 34th Annual Ports, Waterways, Freight, and International Trade Conference, held in May 2009, is how to improve the supply chain and logistics in a carbon-constrained world. Industry experts at the conference agreed on the critical need to explore new and innovative strategies for reducing emissions at intermodal terminals, echoing TRB's call for "bold ideas to meet big challenges." With the same goal in mind, TRB's Intermodal Freight Terminal Design and Operations Committee released a call for papers stating that "there is an urgent need to improve the understanding of existing and emerging technologies and practices that could lead to improved regional air quality, while also maintaining or even enhancing an intermodal terminal's competitiveness." The National Cooperative Freight Research Program has a similar view on promoting good environmental stewardship, as indicated by its support of a research study to "identify and evaluate approaches that can be used by public and private entities to estimate, monitor, and reduce freight emissions and impacts across the supply chain."

Drayage trucks (i.e., diesel-fueled, heavy-duty trucks that transport containers, bulk, and break-bulk goods to and from ports and intermodal rail yards to other locations) play an important role in supply chains. From marine terminals, drayage drivers and trucks transport import containers to first receivers where consolidation, stripping, transfers, and intermodal activities are undertaken. Drayage drivers and trucks also deliver containers to final receivers directly or via key rail intermodal terminals across the nation. This process is reversed for export containers. Drayage operation is widely recognized as a critical emissions, congestion, and capacity issue for major container ports and rail intermodal terminals, and public agencies are rapidly developing policies and programs to reduce related emissions. At the same time, drayage firms and terminal operators are working to improve today's highly inefficient drayage operations. Despite the relatively short distance that trucks move as compared with rail or barge, drayage accounts for a large percentage (between 25% and 40%) of origin-to-destination expenses (*1*). In turn, high drayage costs seriously affect the profitability of intermodal services.

In response to the national call to take bold initiatives to increase supply chain efficiency while reducing carbon emissions, this study investigates how automated transfer management system (ATMS) technology can be used with intelligent transportation system (ITS) technologies and terminals' e-business environments to reduce the in-terminal dwell time of trucks at either seaport container terminals or intermodal facilities. Although ATMS is an emerging technology, ITS and the terminals' e-business environments (e.g., VoyagerTrack and eModal) have been in use for several years; however, they have been largely unexplored in intermodal transport research. These emerging and existing technologies offer numerous research opportunities and challenges. This paper presents a framework for integrating these technologies and using the framework to improve the time it takes for a drayage truck to pick up an inbound container, which is of critical importance in reducing engine idling and stop-and-go lugging. Reducing the drayage trucks' in-terminal dwell time in turn reduces the emission of local and regional greenhouse gases, nitrogen oxides, and fine particulate matter, which is recognized by the U.S. Environmental Protection Agency (EPA) as a serious health issue.

PRIOR RESEARCH

Most research dedicated to seaport terminals has been done recently and is aimed at operational issues. This is because terminals are often seen as bottlenecks in freight transportation, and there is an increasing call for more research to improve their efficiency and

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productivity. Many papers deal with the optimization of specific processes at terminals, such as berth scheduling, crane scheduling, stowage planning and sequencing, storage activities, and allocation and dispatching of yard cranes and transporters (*2, 3*). The majority of the work is focused on marine-side and container-yard activities. Much less research has addressed land-side activities, with some exceptions (*4, 5*).

Most work on rail intermodal facilities is focused on improving operations in regard to the length and utilization of transshipment tracks, train and truck arrival patterns, the type and amount of handling equipment, the mean stacking height in the storage area, the terminal access system and procedures, and the loading of trains (*6, 7*). These studies often use simulation models. Recently, an increasing number of works have addressed the issue of identifying the optimal locations for intermodal freight terminals (*8, 9*).

A few studies have looked at improving drayage operations at both seaport terminals and intermodal facilities. Some researchers have examined whether central planning of all pick-up and delivery trips from several drayage companies in one terminal service area can reduce drayage costs (*10, 11*); others have explored how a single drayage company can move within a local area with one or more terminals carrying as many loads as possible at the least cost (*12, 13*). The methodologies employed in these studies have consisted of a mixture of operations research models (e.g., integer programs) and simulation models.

Only two studies have been found that specifically deal with drayage of import containers with respect to terminals' e-business environment or ITS. Namboothiri and Erera (*14*) assessed the impact of a terminal's appointment system on drayage operations, and Jones and Walton (*15*) examined strategies for stacking import containers to minimize handling effort.

CURRENT PRACTICE

Storage of Import Containers at Seaport Terminals

Terminal operators typically store import containers and export containers in separate yard blocks. A comprehensive review of stacking strategies can be found in Stahlbock and Voß (*16*). As import containers are discharged from a vessel, they are filled bay by bay sequentially in import blocks designated by the yard planner. Unlike export containers, which are segregated by vessel, destination, size, and weight, import containers are stacked in the order they arrive in the yard block. This strategy is designed to facilitate discharge operations and reduce vessel turnaround time, which is the number one priority of the terminal operator. Over time, newer import containers are stacked on top of older ones. Hence, the longer a container has been in storage, the more likely it is to be at the bottom of a stack of containers and the more likely it is to be the next container to be picked up. When a drayage truck arrives in the yard block to pick up a container that is buried at the bottom of a stack, additional moves, called "rehandles," are needed to retrieve the desired container. Figure 1 shows a typical import drayage process at the Port of

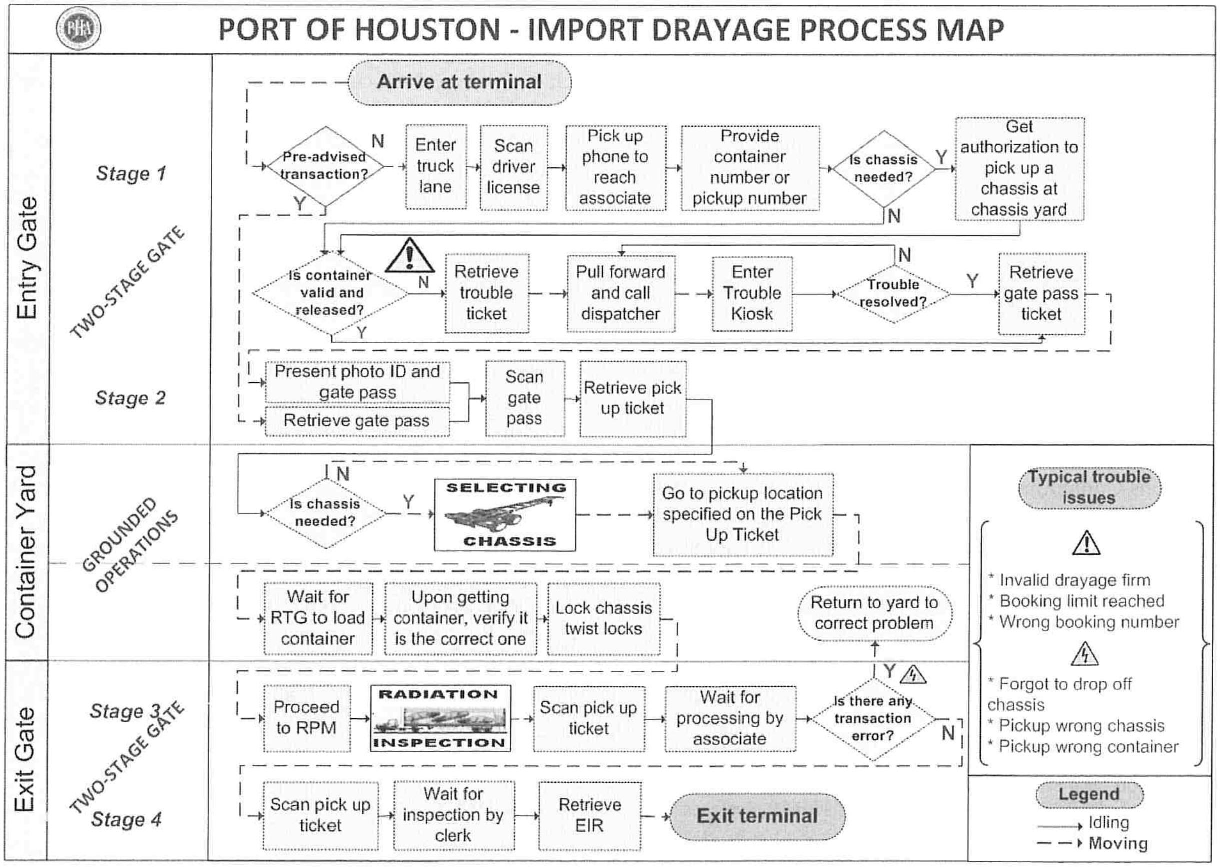

FIGURE 1 Import drayage process at the Port of Houston (developed for NCFRP Project 14 by a research team from Tioga Group, University of Texas–Austin, and University of South Carolina) (RTG = rubber-tired gantry; RPM = radiation portal monitor; EIR = environmental impact review).

Houston, which uses a two-stage gate and stacked operations in the yard. A similar process takes place at a railroad intermodal facility. Some terminals primarily use wheeled operations instead of stacked operations in their yard (e.g., the Port of Los Angeles/Long Beach in California), and some use a single-stage gate instead of a two-stage gate (e.g., APM Terminal at Port Elizabeth in New Jersey).

Terminal Appointment System

Truck appointment systems were first implemented in California ports in July 2003 as a result of California Assembly Bill (AB) 2650. Many terminals did not embrace the appointment system concept but had to comply to avoid paying fines. A study done by Giuliano and O'Brien indicated that "there is no evidence to suggest that the appointment system reduced queuing at terminal gates" (*17*). This and other studies suggest that appointment systems implemented by reluctant terminal operators tend to fail (e.g., terminals in southern California), while those implemented by committed operators tend to succeed (e.g., the Port of Oakland in California, and the Port of Vancouver in Canada). Since the implementation of the PierPASS OffPeak program, which imposes a fee of $50 per 20-ft equivalent unit ($50 for a 20-ft container, $100 for a 40-ft container) for gate arrivals during peak daytime hours and waives the fee for gate arrivals in off-peak hours, fewer terminals in southern California are implementing the appointment system.

POTENTIAL PRACTICE

Automated Container Storage and Retrieval System

An ATMS is an active parking stall and a minicrane designed to help terminal operators facilitate the transferring, discharging, and receiving of containers to and from vessels and terminal, railroad, and truck line carriers. An ATMS has a variety of applications and can elevate, lower, store, and position containers for drayage drivers and crane operators to load or unload without assistance. Figure 2 illustrates how a one-high ATMS works; additional information can be found in Zumerchik et al. (*18*). For a two- or three-high ATMS, cranes load and unload containers from the top position of the ATMS, and drayage trucks load and unload containers from the bottom position of the ATMS. The benefit of an ATMS is that it reduces handling and allows yard equipment and drayage trucks to operate independently of one another, resulting in much faster cycle times for the yard equipment and less time spent inside the terminal for drayage drivers picking up and dropping off containers.

Figure 3 shows the typical process a drayage driver goes through in hooking up a drayage truck to a chassis. Figure 2 shows that the ATMS process is much quicker than the current process (Figure 3). Empirical observations show that these processes take 3 to 5 min and 10 to 15 min, respectively. The reason for the significant difference in process time is that with ATMS, a driver simply backs his chassis into the ATMS, and the ATMS lowers the container onto the truck chassis without any assistance from the crane. In contrast, in the current process, the driver must manually mount the chassis–container onto his tractor and then inspect the chassis and make air and electrical connections. A series of ATMSs that are three-high gives terminal operators far greater crane productivity and container capacity than a conventional chassis yard; however, a planning system is required to ensure that the desired container will be sitting at the bottom position (i.e., the position accessible to drayage trucks) when the drayage driver arrives, a time that is inherently random. In practice, major rail customers such as FedEx, UPS, JB Hunt, and Schneider have a streamlined logistics process in which a truck can pick up any of their inbound containers. The ATMS complements this system. Having a more streamlined logistics process and much shorter free time allowances distinguishes rail operations from marine terminal operations. Thus, the ATMS multicell application modeled here is for a marine container yard.

Informed Storage Strategy for Import or Inbound Containers

To address the aforementioned research question, this study proposes using the framework depicted in Figure 4. By using the terminal appointment system and ITS technologies [i.e., Global Positioning System (GPS) and automatic vehicle location (AVL) technology], priorities could be assigned to containers on the basis of their appointment times and proximity to the terminal. An objective of this research is to ensure that the desired container is in the ready position (i.e., the bottom cell) of the ATMS when it is needed by the drayage truck.

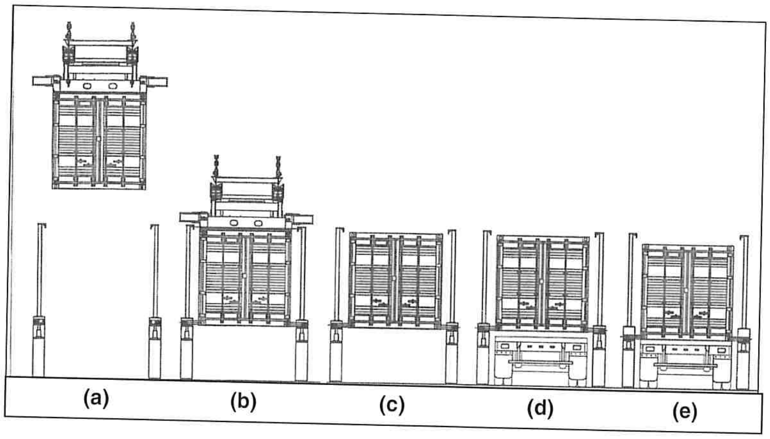

FIGURE 2 Crane–ATMS–truck interface: (*a*) crane unloading inbound container from a railcar, (*b*) crane loading an outbound train, (*c*) awaiting truck pickup for inbound delivery, (*d*) truck chassis backs in to deliver an outbound container for crane to load, and (*e*) truck backs in to pick up an inbound container.

drayage performance. Among them, three are deemed most relevant for this study: (1) crane cycle time (i.e., time required to complete one move), (2) the number of cranes available to provide such service, and (3) the potential delay to drayage trucks caused by freeway congestion. Another intent of this study is to test the hypothesis that the earliest arrival time priority rule (EATPR) will result in better drayage performance than the closest appointment time priority rule (CATPR) by explicitly considering traffic congestion.

For the purpose of this investigation, only one crane is available for the single block, and it has very little lead time because of the marine terminal operator's policy of accepting same-day appointments. Ideally, the appropriate number of cranes would be made available depending on the number of containers in the block. A period of 8 h is examined. However, the length of each replication is 10 h. This is done to ensure that all trucks exit the system by the time the simulation ends. For each experiment, 100 replications are performed. A hypothetical drayage–port environment with the following parameters is used for testing purposes. The triangular distribution (TRIA) is assumed for all cases, which is characterized by three parameters (minimum, mode, maximum); the TRIA has been found to be the best fit distribution for several key terminal operational processes (*22*). The values related to terminal operations are typical values observed at the Port of Houston in Texas:

- Travel time to terminal: TRIA (20, 30, 45 min);
- Delay due to congestion: TRIA (0, 15, 60 min);
- Entry gate processing: TRIA (2, 3, 5 min);
- Gate-to-yard and yard-to-gate travel time: TRIA (3, 5, 10 min);
- ATMS processing: TRIA (3, 4, 6 min); and
- Exit gate processing: TRIA (5, 8, 15 min).

In addition, the experiments assume that 10 appointments are made every 0.5 h and that there are a sufficient number of three-high ATMSs to accommodate the appointment requests. The metric to be used to compare the performance of the two priority rules is truck turn time, which refers to the time it takes a drayage truck to complete a transaction such as picking up an import or inbound container or dropping off an export or outbound container. In this study, the truck turn time starts when the truck comes through the entry gate and ends when the truck departs the exit gate.

ANALYSIS OF RESULTS

Drayage Operations

To provide a benchmark for comparison, truck turn time under the ideal scenario is obtained. The ideal scenario is considered to be when the drayage driver does not encounter any delay while picking up the import or inbound container from the ATMS. Using the assumed distributions and values, truck turn time under the ideal scenario is 29.00 min. The corresponding 95% half-width value (i.e., half-width of a 95% confidence interval) is equal to 0.05, which suggests that the length of each replication and the number of replications used is adequate.

TABLE 1 Delay Caused by Congestion: Results for CATPR

Crane Loading Time of One Container into ATMS (min)			Avg. Turn Time (min)	95% Half-Width	Crane Utilization (%)
Min.	Mode	Max.			
TRIA (0, 15, 60 min)					
1	2	3	37.49	0.98	53
1	2.5	4	48.17	1.19	67
1	2.5	4.5	54.71	1.62	71
1	3	5	102.96	6.77	80
1	3.5	5	193.55	9.58	84
1.5	3.5	5	275.48	4.69	89
TRIA (0, 15, 30 min)					
1	2	3	45.06	1.15	53
1	2.5	4	66.49	1.96	66
1	2.5	4.5	78.96	2.17	71
1	3	5	178.09	9.3	80
1	3.5	5	274.54	5.9	85
1.5	3.5	5	307.90	2.47	89

Table 1 shows the results corresponding to CATPR. The results illustrate the effect of crane cycle time and delays caused by congestion on the truck turn time and crane utilization. Note that crane cycle time will be lower with ATMS because there is no waiting on trucks to position their chassis, nor is there a need to lower the container all the way down to chassis level. The top half of Table 1 indicates that the average turn time is quite sensitive to crane cycle time. The exceedingly long turn time is due to the inability of a single crane to keep up with the number of incoming requests. Note the increase in crane utilization as the crane loading time increases. When the crane utilization exceeds 70%, the truck turn time increases dramatically.

The results in the bottom half of Table 1 show the effect of less congestion on truck turn time (note that the maximum value is changed from 60 to 30 min). Although crane utilization is nearly the same as before, turn time is higher. This is because the crane now has even less time to complete its backlog of work before the drayage truck reaches the terminal, delaying the drayage truck.

Tables 2 and 3 show the results corresponding to EATPR. With the same values for the crane loading time, it can be seen that the truck turn time when using EATPR is much lower than when using CATPR. These results confirm the hypothesis. Intuitively, it makes sense that EATPR outperforms CATPR because the terminal operator will want to load the ATMS to accommodate those drayage trucks that will arrive at the terminal first. The reason why CATPR performs poorly is because trucks with earlier appointments could be delayed—perhaps because of traffic, a problem at the distribution center, or a delay while picking up a chassis at a separate terminal. Ideally,

TABLE 2 Delay Caused by Congestion (TRIA 0, 15, 60 min), One Loading Crane: Results for EATPR

Crane Loading Time of One Container into ATMS (min)			Avg. Turn Time (min)	95% Half-Width	Crane Utilization (%)
Min.	Mode	Max.			
1	2	3	29.99	0.05	53
1	2.5	4	29.01	0.05	67
1	2.5	4.5	29.13	0.12	71
1	3	5	32.22	0.95	80
1	3.5	5	62.94	5.51	84
1.5	3.5	5	147.34	7.22	89

TABLE 3 Delay Caused by Congestion (TRIA 0, 15, 60 min), More Than One Loading Crane: Results for EATPR

Crane Loading Time of One Container into ATMS (min)			Avg. Turn Time	95% Half-	Crane Utilization	Additional
Min.	Mode	Max.	(min)	Width	(%)	Cranes
1.5	3.5	5	63.10	3.11	74	⅓
1.5	3.5	5	35.44	0.91	64	½
1.5	3.5	5	29.01	0.05	44	1

trucks would enter the ATMS terminal with their own chassis and then drop off containers at the distribution centers with ATMS bays. In such a scenario, traffic delays will be the only remaining uncertainty in port drayage operations. Carrier ownership of the chassis is best to ensure the chassis and tractors are in safe working condition. Carrier ownership also eliminates the problems of phantom damage claims to the chassis and liability exposure for the railroads, ports, and ship lines. It also ends the costly chassis processes ongoing at terminals, as outlined in Figures 1 and 3.

As illustrated in Tables 1 and 2, the turn times yielded by EATPR are significantly lower than the turn times yielded by CATPR. Operationally, these results indicate that having the terminal operator employ EATPR better facilitates the flow of drayage trucks through the gate and yard. In particular, trucks spend minimal time retrieving their desired container because it already has been lowered to the bottom position of the ATMS. When the terminal employs CATPR, truck arrivals may not be in the same order in which containers had been preloaded into the ATMS on the basis of their appointment times. In this situation, the red flashing light of the ATMS would notify yard tractor drivers to remove the bottom container and place it in a delinquent appointment ATMS. A late pickup fee would serve as a disincentive for tardiness.

The results in Table 3 show the potential improvement in truck turn time if there are additional crane resources to provide service to the ATMS. In the one-crane case, truck turn time is 147.34 min [for crane loading time = (1.5, 3.5, 5 min)]; with another crane assisting for a third of a day, turn time is reduced to 63.10 min. If another crane is available to assist for half a day, the turn time improves to 35.44 min. Lastly, with another crane assisting for the entire day, the turn time is reduced to 29.01 min, which matches our benchmark value in the ideal scenario.

Emissions Reduction

The modeling results and empirical observations indicate that the ATMS will save at least 10 min of in-terminal dwell time for a drayage truck in wheeled operations and save significantly higher time for a drayage truck in stacked operations because of the need for the drayage truck to wait for a crane and the likely rehandles. Using the generic default values in the DrayFLEET model, which is equivalent to the Port of Virginia environment, a reduction of 10 min of turn time at the seaport terminal translates to a reduction of 14.9% in idle time and 0.9% to 1.5% in related emissions. If ATMS were employed at both the marine terminal and the rail terminal, the combined benefit would translate to a reduction of 16.3% in idle time and 1.0% to 1.6% in related emissions. The reduction would be even greater if ATMS were employed at the distribution centers as well. Tables 4 and 5 provide a summary of the emissions results. While these reductions are small at the regional level, the collective reduction at the national level may be much greater than the sum of its parts. In addition, the 10-min reduction is a very conservative estimate of the potential time saving because it considers only the transfer process. When considering the general drayage process, in which drivers have to search for a suitable chassis or may receive a bad chassis, the use of ATMS will yield significantly more time saving. Moreover, ATMS communication and security features will also permit no-delay automated entry and exit gates, further improving truck turn times.

TABLE 4 Emissions Reduction Resulting from Faster Turn Time: Scenario 1 (Marine Terminal Only)

	Emission Output (annual tons)			
	Base Case (30 min of turn time)	Scenario 1 (−10 min of turn time)	Change	% Change
HC	55	54	−0.78	−1.4
CO	311	306	−4.65	−1.5
NO_x	1,154	1,142	−11.97	−1.0
PM_{10}	38	38	−0.36	−0.9
$PM_{2.5}$	32	32	−0.30	−0.9
CO_2	145,037	143,600	−1,437.13	−1.0

NOTE: HC = hydrocarbons, CO = carbon monoxide, NO_x = nitrogen oxides, PM_{10} = particulate matter ≤ 10 micrometers diameter, $PM_{2.5}$ = particulate matter ≤ 2.5 micrometers diameter, CO_2 = carbon dioxide.

TABLE 5 Emissions Reduction as a Result of Faster Turn Time: Scenario 2 (Marine Terminal Plus Rail Terminal)

	Emission Output (annual tons)			
	Base Case (30 min of turn time at marine terminal, 20 min of turn time at rail terminal)	Scenario 1 (−10 min of turn time at marine terminal, −10 min of turn time at rail terminal)	Change	% Change
HC	55	54	−0.86	−1.6
CO	311	306	−5.07	−1.6
NO_x	1,154	1,141	−13.04	−1.1
PM_{10}	38	38	−0.39	−1.0
$PM_{2.5}$	32	32	−0.33	−1.0
CO_2	145,037	143,470	−1,566.58	−1.1

CONCLUSIONS AND PRACTICAL CONSIDERATIONS

This study investigated how ATMS and its robust communication abilities can be combined with ITS technologies and terminals' e-business environments to reduce trucks' in-terminal dwell time at either seaport container terminals or intermodal facilities. It presented a framework for integrating these technologies and applying the framework to improve the time it takes for a drayage truck to pick up an inbound container. The proposed framework was used to investigate the effect of the priority rules for loading containers into the

ATMS to improve drayage operations. The analysis of the priority rules was assisted by a computer simulation model developed specifically for this study.

Results confirmed the hypothesis that EATPR yields better drayage performance than CATPR for the multilevel ATMS. However, if the cranes work independently and well ahead of the appointments (assuming appointments are made well in advance), crane and drayage productivity would be much better. The analysis demonstrated the usefulness of the simulation model in understanding the effects of congestion and additional resources. While some general conclusions can be drawn from the presented model, quantifiable improvements are not valid because of the assumed generic distributions and values. Moreover, the model made some strong assumptions: that all trucks seek to honor their appointments, that all trucks originate within 30 min of the terminal, and that the terminal did not feature an optimal ATMS design for the simulation.

ATMS, with its ability to eliminate rehandles, could be a bold first step in a new era of super-efficient intermodal transport. However, research is needed to develop intelligent strategies and algorithms to make ATMS work seamlessly with the current and emerging environments. For example, consider the scenario whereby a driver misses his appointment for the bottom container and another driver comes for the above container. The terminal design–operation model considered in this work is one in which the terminal operator attempts to have all containers preloaded into the ATMS in the exact order of truck arrivals. An alternative model would be to have a late pickup area. When a driver misses his appointment, a yard tractor would unload the bottom container and bring it to a late pickup area that uses a single-high ATMS. The late driver then would pick up his container at the late pickup area. Another possible model that does not employ a late pickup area is to have a good mixture of one-, two-, and three-high ATMSs. The three-highs and two-highs could be dedicated to major customers such as Wal-Mart, Target, and UPS and customers that consistently keep their appointments. The one-high ATMS could be used for the more immediate appointments and late pick-ups. The right mixture is a design question that terminal operators will need to consider. Each of the three aforementioned design–operation models has advantages and disadvantages, and more research is needed to help terminal operators find the right one for their environment. Finally, research is needed to determine the optimal number of ATMSs for a terminal to ensure that its cranes are always working independently and well ahead of the expected truck traffic.

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Scheduling of Inbound and Outbound Trucks at Cross-Docks

Modeling and Analysis

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A model is developed for both time and space scheduling of inbound and outbound trucks at a cross-dock facility under various objectives. Three different objectives in optimizing cross-dock operations are presented, and the justification for the use of these objectives is given. A linear mixed integer formulation of the problem is presented, and a restriction–approximation approach is developed and applied to determine the truck scheduling at a sample cross-dock facility. This paper also analyzes the behavior of each of the objectives and provides a comprehensive analysis of the results. Pareto and post-Pareto analyses of the multiobjective problem are presented.

A cross-dock is a materials handling and distribution facility where products are unloaded from inbound trucks (ITs) or rail cars, sorted, consolidated or deconsolidated, and reloaded into outbound trucks (OTs) or rail cars, with little or no storage in between. Products typically leave a cross-dock within 24 h of arrival and often leave in less than 1 h. Cross-docking reduces unnecessary warehousing, handling, and transportation costs by streamlining supply chain operations and expediting the delivery process. Growing service requirements for fast delivery, flexibility, and low costs have resulted in the increased popularity of the cross-docking concept. Most of the pertinent research attempts to optimize different aspects of cross-docking operations and improve overall system performance.

Several articles in the literature focus on the assignment of trucks to doors and the arrangement of inbound doors (IDs) and outbound doors (ODs) to optimize the travel distance of materials inside the cross-dock facility. Aickelin and Adewunmi aimed to identify the optimal arrangement of a cross-dock center's IDs and ODs and determine the most efficient assignment of destinations to ODs (*1*). Others have studied the trailer assignment problem and determined the best cross-dock facility shape considering congestion inside a cross-dock (*2–4*). All of these works aimed to minimize the travel distance of equipment or labor inside the facility, which are surrogates for labor cost and cycle time. By minimizing the total distance traveled inside the facility, terminal productivity could be improved and operation efficiency enhanced (*5–7*). Vis and Roedberger tried to minimize the travel distances of forklift trucks carrying loads in order to find the proper location for products in a cross-dock facility (*8, 9*). Bozer and Carlo indicated that for a given volume of freight, processing time primarily depends on travel time, which is a function of distance traveled inside the facility (*10*). Gue minimized the weighted freight travel distance and measured the effect of trailer scheduling on the layout of a facility (*11*).

Several additional articles deal with the optimization of service time. Alvarez-Perez et al. and Li et al. claimed that in a just-in-time (JIT) environment, having the jobs finished by the exact time requested by the customer is desirable, and thus the objective of JIT scheduling is to minimize penalties for early or late finishing (*12, 13*). Boysen et al. claimed that the efficiency of a cross-docking system mostly depends on the coordination of inbound and outbound flows (*14*). Therefore, they solve a sequencing problem to reduce the delay of shipments at the cross-dock by minimizing the total completion time of operation (referred to as "makespan" in scheduling). By holding the same objective of minimizing the total completion time, various authors have been able to minimize the makespan of cross-docking and minimize the weighted completion time (*15–18*). Similarly, Yu and Egbelu minimized total operation time to find the best truck door assignment and scheduling sequences (*19*). Wang and Regan minimized the time freight spends in a cross-dock by studying the truck scheduling problem, and Wang et al. scheduled ITs to minimize departure of OTs, a surrogate for minimizing the time freight spends in a cross-dock (*20, 21*). Lim et al. minimized the total shipping distance of freight inside a cross-dock facility (*22*). Miao et al. aimed to find an optimal scheduling of trucks that minimizes the operational cost of the cargo shipments and the total number of unfulfilled shipments at the same time (*23*). In summary, the main objectives of cross-docking are to reduce operating costs (which are primarily affected by the labor cost of cross-docking) and minimize the makespan and optimize the handling process of freight between IDs and ODs. This translates into minimizing the (weighted) travel distance of workers, forklifts, and freight.

Cross-docking may be classified according to different criteria. It may be classified on the basis of whether or not freight is already assigned to a customer, creating the categories of predistribution cross-docking and postdistribution cross-docking. It may also be classified by the shape of the facility. The traditional and most common is the "I" shape; other shapes such as "L," "T," "H," and "U" are also used.

This paper develops a model for scheduling of ITs and OTs and addresses three main objectives covered by the existing literature on predistribution, I-shaped cross-dock facilities. This paper also analyzes results under each objective and under a multiobjective approach. The remainder of the paper is organized as follows. The problem under consideration and the objectives considered in the mathematical formulation of the problem are discussed. A mixed-integer program (MIP) formulation of the problem is presented. Numerical examples

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and a restriction–approximation approach used in the solution of the problem are given. The results from the analysis of the numerical examples are discussed, first for each objective considered in the problem and then for the multiobjective formulation. Finally, a summary of the findings and concluding remarks are presented.

PROBLEM DESCRIPTION AND OBJECTIVES

In general, materials flow through a cross-dock facility in the following manner: ITs arrive at the cross-dock, are assigned to an ID, and are then sequenced to unload their products. This process is known as IT scheduling and is the main part of ID operations (*24*). A similar assignment and sequencing process takes place for OTs arriving at ODs, which is part of OD operations. The movement of products from IDs to ODs is part of the internal operations of cross-docking. This paper considers the scheduling of both ITs and OTs with the goal of optimizing inbound, outbound, and internal cross-dock operations.

Minimizing total service time and departure time (or tardiness) are the main objectives of the truck sequencing problems addressed in the literature; minimizing the total travel distance or weighted distance within the facility are the main objectives of the truck door assignment problems. Most of the formulations considered in the literature treat each problem individually, and none of them address both truck sequencing and door assignment together while treating ITs and OTs simultaneously. The formulation presented in this paper considers the problem of truck scheduling with three objectives, specified as follows:

1. Minimize total starting and handling times of serving ITs at the IDs,
2. Minimize total weighted travel distance of pallets inside the facility, and
3. Minimize total departure time of OTs at the ODs.

These objectives deal with ID operation, inside operation, and OD operation, respectively. The following sections discuss the advantages of optimizing these three objectives.

Minimize Total Starting and Handling Times of Inbound Trucks

Cross-docking starts when ITs with products arrive at the facility and ends when the products are loaded onto the OTs (*25*). For typical predistribution cross-docking, before the arrival of ITs, an ID has to be allocated. By means of real-time information technology, the arrival times of ITs are known a priori. Upon the arrival of ITs, trucks are either directly assigned to an ID or need to wait in an assigned parking space in front of the IDs. Waiting is caused by a limited amount of resources, including equipment, workers, and doors at the facility (*14*). For all ITs, late starting means unproductive waiting time. The performance of ID operation could be measured by how fast the ITs are served given a fixed amount of resources. ITs will leave as soon as they finish unloading; thus, their early departure translates into smaller waiting and handling times and faster service. There are three reasons to minimize the total starting and handling times of ITs. First, an efficient schedule of serving ITs reduces the makespan of the whole operation, including the departure of OTs. Second, if the number of ITs that are not assigned directly to IDs is high, it may exceed the capacity of the available parking near the ID area. Capacity expansion is costly; thus, the best option is to improve the efficiency of accommodating ITs and reduce their waiting time. Finally, the late start of truck services means unproductive time for truck drivers and a reduced potential for them to increase their revenue. Early starting time does not necessarily mean short unloading handling time, however; therefore, the objective should be to minimize both.

Minimize Total Weighted Travel Distance

Commodities unloaded from ITs need to be moved to ODs and loaded onto OTs, either directly, after being staged on the dock, or after reconfiguration. One way to measure cross-docking performance is to estimate the total travel distance between IDs and ODs of all products (*3*). Bartholdi and Gue present two methods for evaluating this performance. One is simply to look at the distances between each pair of IDs and ODs; the other is to look at the weighted travel distance. In the past, most of the studies considered the ID-to-OD distance (*3*). Technology implementation provides the cross-dock operator with full information on product flow within the facility, enabling the use of weighted travel distance as a measure, resulting in a more detailed and reasonable evaluation of cross-docking performance. In addition, the use of cross-docking is effective as long as its total operating cost is less than the savings from reduced inventory and transportation cost. Operating costs, including labor costs, are directly related to travel distance, which is affected by the assignment of ITs and OTs to doors. Therefore, operating costs can be reduced by minimizing the total weighted travel distance.

Minimize Total Departure Time of All OTs

If the starting time of the first IT arrival is set as time zero, then the departure time of the last OT can be regarded as the makespan. Therefore, minimizing departure time of the OTs can indirectly minimize the makespan of the whole cross-docking operation, which includes the travel time, handling time, and waiting time of products inside the facility (*20, 21*). In Wang et al., the authors present the relationship between the departure of OTs and freight wait time (*21*). Accelerating the departure time of OTs decreases the time freight spends inside the facility. In addition, assuming the OD can be used for loading another OT as soon as the previous OT departs, minimizing the departure time of the previous OT can indirectly reduce the waiting time of its immediate successor. Similar to scheduling of ITs at IDs, a long waiting time for OTs tires drivers and leads to discontent (*24*). Departure time is one of the crucial measurements of throughput for cross-docking operations.

In summary, minimizing the total starting and handling times of ITs offers benefits to ID operations. However, considering this as the sole objective may lead to increased total weighted travel distance inside the facility. In this case, the ITs will be assigned to IDs without consideration of the physical location of either doors or staging areas, which leads to increased travel distance of pallets from the IDs to the ODs. However, minimizing this travel distance degrades the optimality of total starting and handling times. Because the OD operation starts after the ID operation and the inside operation, both scheduling of trucks and the travel distance of products affect the performance of the OD operation. Therefore, to best schedule the ITs and OTs and create an optimal solution to the problem, it is necessary to balance all objectives.

MATHEMATICAL MODEL

The model discussed herein considers the scheduling of ITs and OTs at an I-shaped cross-docking facility with IDs and ODs positioned along the long side of the facility (see Figure 1). The study assumes a predistribution cross-docking arrangement, which means that the freight flow from each IT to each OT is known a priori. Other assumptions are listed as follows:

1. Each door is predefined as an ID or OD.
2. The internal product-moving equipment can transfer a fixed number of pallets at a time from an ID to an OD (e.g., one pallet per move).
3. The handling time of a pallet is independent of the commodity type.
4. Following the unloading from ITs, the products are available in the area adjacent to the ID to be transferred to the OD.
5. Loading of an OT starts once all the products to be loaded are available in the area adjacent to the assigned OD.
6. Travel time per unit distance between every pair of IDs and ODs is equal.
7. There is an adequate amount of internal equipment and an adequate number of laborers to move products.

Index

i	All IDs $i = 1, 2, \ldots, I$
j	All ITs $j = 1, 2, \ldots, J$
m	All ODs $m = 1, 2, \ldots, M$
l	All OTs $l = 1, 2, \ldots, L$
k, k'	Serving order for trucks $k = 1, 2, \ldots, K$

Parameters

ITAT_j	Arrival time of IT j
OTAT_l	Arrival time of OT l
$C_{j,i}$	Handling time for IT j at ID i
$H_{l,m}$	Handling time for OT l at OD m
$V_{j,l}$	Freight flow (number of pallets) from IT j to OT l
$DV_{j,l}$	Binary matrix; if $V_{j,l} > 0$, $DV_{j,l} = 1$; otherwise 0
$d_{i,m}$	Distance between door i and door m
speed	Time to move a unit-pallet per foot
M	Large positive number

Decision Variables

$x_{j,i,k}$	Binary variable, $x_{j,i,k} = 1$ if IT j is served at door i as the kth truck; otherwise 0
$y_{l,m,k}$	Binary variable, $y_{l,m,k} = 1$ if OT l is served at door m as the kth truck; otherwise 0
$f_{j,i,m,l}$	Nonnegative variable, pallet flow between i and m when IT j is assigned at ID i and OT l is assigned at OD m
$\text{ITTS}_{j,i,k}$	Nonnegative variable, starting time of unloading IT j at door i as the kth truck if j is served at door i as the kth truck; otherwise 0
$\text{OTTS}_{l,m,k}$	Nonnegative variable, starting time of loading OT l at OD m as the kth truck if l is served at OD m as the kth truck; otherwise 0
TD_l	Departure time of OT l

Objectives

Minimize the total starting time and handling time of all ITs:

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K}\left(\text{ITTS}_{j,i,k} + C_{j,i} \cdot x_{j,i,k}\right) \tag{1}$$

Minimize the total weighted travel distance by freight:

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{m=1}^{M} f_{j,i,m,l} \cdot d_{i,m} \tag{2}$$

Minimize the total departure time of OTs:

$$\sum_{l=1}^{L} \text{TD}_l \tag{3}$$

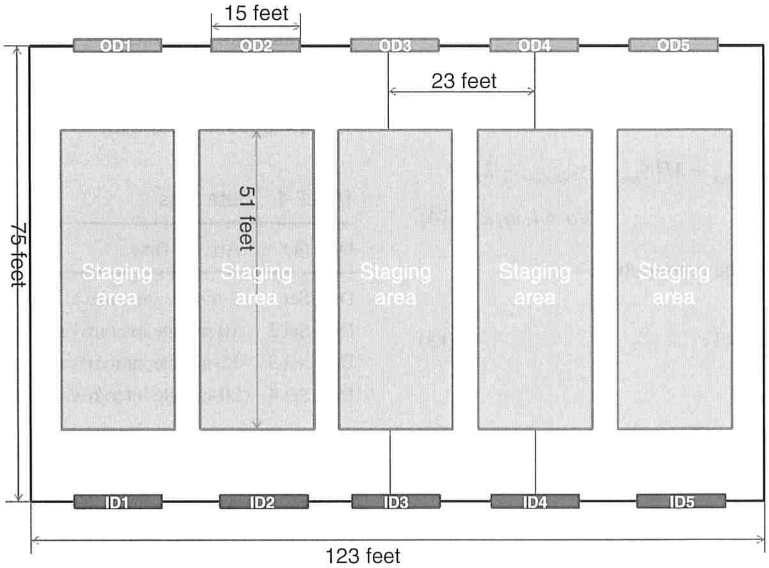


FIGURE 1 Cross-dock facility layout.

Constraints

Each IT and OT will be served only once.

$$\sum_{i=1}^{I}\sum_{k=1}^{K} x_{j,i,k} = 1 \qquad \forall j \qquad (4)$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} y_{l,m,k} = 1 \qquad \forall l \qquad (5)$$

Each ID and OD cannot serve more than one IT or OT at the same time.

$$-M \times \left(1 - x_{j,i,k}\right) + x_{n \neq j,i,k} \le 0 \qquad \forall n \neq j, i, k \qquad (6)$$

$$-M \times \left(1 - y_{l,m,k}\right) + y_{o \neq l,m,k} \le 0 \qquad \forall o \neq l, m, k \qquad (7)$$

Freight flow constraint is represented as follows: the flow from i to m when j is assigned to i and l is assigned to m equals the flow $V_{j,l}$. For all other $f_{j,i,m,l}$ it is zero.

$$V_{j,l} - f_{j,i,m,l} \le M\left(2 - x_{j,i,k} - y_{l,m,k'}\right) \qquad \forall j, i, k, l, m, k' \qquad (8)$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} f_{j,i,m,l} = V_{j,l} \qquad \forall j, l \qquad (9)$$

The starting time of serving ITs and OTs should be later than the truck arrival time and should be zero if an IT or OT is not served at an ID or OD (i/m).

$$\text{ITAT}_j \cdot x_{j,i,k} \le \text{ITTS}_{j,i,k} \le Mx_{j,i,k} \qquad \forall i, j, k \qquad (10)$$

$$\text{OTAT}_l \cdot y_{l,m,k} \le \text{OTTS}_{l,m,k} \le My_{l,m,k} \qquad \forall l, m, k \qquad (11)$$

The starting time of loading an OT should be after the time the last commodity is ready to be loaded.

$$\text{OTTS}_{l,m,k'} \ge \left(\text{ITTS}_{j,i,k} + C_{j,i} \cdot x_{j,i,k}\right)DV_{j,l} + \text{speed} \cdot f_{j,i,m,l} \cdot d_{i,m} - M\left(1 - y_{l,m,k'}\right) \qquad \forall j, i, l, m, k, k' \qquad (12)$$

The starting time of serving an IT or OT as the (k + 1)th truck should be no earlier than the service finish time of its predecessor.

$$\text{ITTS}_{n \neq j,i,k+1} \ge \text{ITTS}_{j,i,k} + C_{j,i} \cdot x_{j,i,k} + M\left(x_{j,i,k} + x_{n \neq j,i,k+1} - 2\right) \qquad \forall n \neq j, i, k \qquad (13)$$

$$\text{OTTS}_{o \neq l,m,k+1} \ge \text{OTTS}_{l,m,k} + H_{l,m} \cdot y_{l,m,k} + M\left(y_{l,m,k} + y_{o \neq l,m,k+1} - 2\right) \qquad \forall o \neq l, m, k \qquad (14)$$

The order at the ID and OD must be consecutive.

$$k \times x_{j,i,k} \le \sum_{n \neq j}^{J}\sum_{h<k}^{K} x_{n,i,h} \qquad \forall j, i, k > 1 \qquad (15)$$

$$k \times y_{l,m,k} \le \sum_{o \neq l}^{L}\sum_{h<k}^{K} y_{o,m,h} \qquad \forall l, m, k > 1 \qquad (16)$$

Define the departure of an OT.

$$\text{TD}_l \ge \text{OTTS}_{l,m,k} + H_{l,m} \times y_{l,m,k} - M \times \left(1 - y_{l,m,k}\right) \qquad \forall l, m, k \qquad (17)$$

$$\text{TD}_l \ge 0 \qquad \forall l \qquad (18)$$

NUMERICAL EXAMPLES AND SOLUTION APPROACH

Data

- Dimensions and distance. Cross-dock dimensions are based on the work of Wang et al. and Sandal (*21, 26*). The width of the cross-dock is 75 ft, and each door has a width of 15 ft with an 8-ft distance between neighboring doors. The cross-dock has five doors on each side, with a total length of 123 ft (Figure 1).
- Arrival time. A small-size cross-dock facility with 10 doors (five IDs and five ODs), scheduled for 20 trucks (10 ITs and 10 OTs). The arrival time for ITs is exponentially distributed with different interarrival times of 5, 10, 15, 20, 25, 30, and 35 min. The arrival time for all OTs is generated based on the arrival time of ITs (i.e., Data Sets 1–7).
- Handling time. The unloading time of ITs at each door is randomly generated as being between 30 and 60 min (except for Data Sets 4 and 5). In order to see the behavior of extreme cases in the computational results, an unloading time of 60 min is given to one of the IDs (ID 1) for Data Set 4. For Data Set 5, 60 min of unloading time is given to ID 1 and 20 min of unloading time to ID 2. Handling time should be realistic, but Data Sets 4 and 5 are used to check model performance in some extreme cases. According to Bartholdi and Hackman, the loading time is usually longer than the unloading time (approximately 1.5 to 2 times longer); therefore, the loading time of OTs at each door is randomly generated as being from 45 to 90 min (*27*).
- Freight flow. According to Wang et al., all ITs and OTs in these examples carry 28 pallets (*21*). The binary matrix associated with the freight flow is thus generated.

A summary of the data considered in each data set is shown in Table 1.

Solution Approach

As with many scheduling problems, the problem considered in this study is nondeterministic polynomial-time hard (NP-hard) and can be solved to optimality only for small instances (*10, 28, 29*). When the problem size (i.e., the number of doors and trucks) increases, the computational time increases exponentially. To solve the problem using exact methods (within 24 h), size limitations are found for each objective. Size limitations were as follows: for the first objective, six ITs and six OTs, with five IDs and five ODs; for the second

TABLE 1 Data Sets

Data Set	Arrival Time	Unloading Time
Data Set 1	5-minute interarrival	All IDs between 30 and 60 minutes
Data Set 2	10-minute interarrival	All IDs between 30 and 60 minutes
Data Set 3	15-minute interarrival	All IDs between 30 and 60 minutes
Data Set 4	20-minute interarrival	ID1 60 minutes, other IDs between 30 and 60 minutes
Data Set 5	25-minute interarrival	ID1 60 minutes, ID2 20 minutes, others between 30 and 60 minutes
Data Set 6	30-minute interarrival	All IDs between 30 and 60 minutes
Data Set 7	35-minute interarrival	All IDs between 30 and 60 minutes

NOTE: For all data sets: number of doors = five IDs and five ODs; number of trucks = 10 ITs and 10 OTs; loading time: all ODs between 45 and 90 min. All data sets consider the same facility dimensions and total freight flow.

objective, nine ITs and nine OTs, with five IDs and five ODs; and for the third objective, five ITs and five OTs, with four IDs and four ODs. The computer processing time for solving these examples was 88.25 s, 4,245 s, and 3.4 h for the first, second, and third objectives, respectively.

Because this problem is difficult to solve, and in order to restrict its dimension and not just its solution space, a restriction–approximation solution is proposed. The suggested approximation restricts the maximum number of k in the model, where k is the order of trucks served at each door (k also represents the maximum number of trucks served at each door in the model). Because 10 trucks and five doors are considered for the numerical examples presented here, and assuming that all the doors will be used at least one time, the maximum k could be restricted by the following equation:

$$k = \text{number of trucks} - \text{number of doors} + 1 = 10 - 5 + 1 = 6 \qquad (19)$$

This means that the valid upper bound of k is much less than the maximum number of trucks. The value of k could be restricted further, assuming that each door will serve an equal number of trucks, if the following equation is applied:

$$k = \frac{\text{number of trucks}}{\text{number of doors}} = \frac{10}{5} = 2 \qquad (20)$$

To demonstrate that $k = 2$ is a reasonable restriction, different examples are run for $k = 2, 3, \ldots, 6$ (defined by Equation 19) or until the same objective function value for k and $k + 1$ results, or the processing time exceeds 24 h. Running examples for $k = 2, 3, \ldots, 6$ shows the trend of the relationship between processing time and objective function value for different k values. If the objective function values for k and $k + 1$ are equal, it means that by further increasing the value of k, the value of the objective function will not increase. If the processing time for solving an example using a larger k exceeds 24 h and little improvement in the optimal value of the objective function is observed for previous k values, it is not worth further increasing k.

Tests are run on Data Sets 1 and 7 by solving only for the first objective function; when the value of k is increased, the computational time increases dramatically. However, the value of the objective function decreases marginally. None of the examples needed to run until $k = 6$. For Data Set 1, processing time exceeds 24 h when using $k = 5$. For Data Set 7, when using $k = 2$, processing time is about 71 s, and the value of the objective function (OF) is 2,386.89. If k is increased to $k = 3$, processing time is about 1,765 s, and the value of the OF is 2,364.58. This means that between $k = 2$ and $k = 3$, processing time increases by more than 2,300%, while the OF value improves only by less than 1%. If k is increased to $k = 4$, processing time becomes about 7,862 s, and the value of the objective function is 2,346.53. The relative difference in OF value between $k = 2$ and $k = 4$ is 1.69%. The large increase in processing time and the minor improvement in OF value do not justify the use of a larger k value. Therefore, the $k = 2$ restriction–approximation for the first objective is reasonable and realistic. To obtain realistic assignments for the OTs, the following constraint in the model is considered.

$$\text{starting time of serving OT} \leq \text{arrival time} + t \qquad (21)$$

Practically, the time limit t in the above equation should be within 30 to 40 min. This means that the OTs should not wait more than 30 to 40 min to be served. Ideally, the value of t for every data set should be as small as possible for the OTs to be served as early as possible. However, the value of t influences the feasibility of the sample problems. Therefore, the minimum t values that make the examples feasible for every data set must be found.

For the second objective, which optimizes the weighted travel distance, an exact solution approach does not produce realistic results, as all ITs are assigned to the same ID and all the OTs are assigned to the same OD, the one facing the selected ID. This outcome is expected because the truck service time is not considered. The resulting distance, however, between ID and OD is always the minimum of 75 ft. Constraint 21 is introduced with $t = 40$, and the problem is solved for the second objective and for $k = 10$, which relaxes the model and gives it more flexibility. This approximation, however, does not produce a feasible solution within 24 h. Reducing the value of k to $k = 2$ results in assigning equal numbers of trucks to each door and restricts the model from assigning all the ITs and OTs to a single ID or OD, producing a more realistic solution.

For the third objective, the $k = 2$ approximation does not work for minimizing the total departure time of all OTs. To solve the problem, however, the following must be considered. Departure time of an OT is the sum of the starting time and the service time of the OT. The starting time of serving an OT is affected by the starting time of serving ITs, the servicing time of ITs, and the transferring time of pallets, all of which have been optimized by the first and second objectives. Thus, to minimize the total departure time of all OTs, an approximation is used that minimizes the service time of all OTs. Constraint 21 is added to make sure that the OTs will not wait too long to be served. The minimum feasible time t is used.

All the computation results are obtained by using the MIP solver ILOG CPLEX 10.1. The computer used to run CPLEX is equipped with an AMD Athlon 64-bit processor with 2.39 GHz and 1.37 GB of random-access memory.

RESULTS ANALYSIS

By using the restriction–approximation presented in the above section, every data set is solved by optimizing one objective at a time and solving for the resulting value of the other objectives. The purpose for optimizing each of the objectives separately is to perform a sensitivity analysis to examine the behavior of each objective. The results are shown in Table 2 and are discussed in the following sections. Following the analysis of individual objectives, a multiobjective analysis is performed in which all three objective functions are considered.

It should be noted that the assumption of an adequate number of laborers and equipment allows the utilization of all cross-dock doors. If there are not adequate resources at the IDs and ODs, this model can be used considering a reduced number of functioning doors of the cross-dock facility to capture the effects of the resulting congestion.

Sensitivity Analysis

Table 2 shows that when the arrival time interval of ITs increases, the total starting and handling times increase accordingly. The first objective function value is 672.11 min for a 5-min interval (Data Set 1) and 890.72 min for a 10-min interval (Data Set 2). When the arrival time interval increases to 30 min (Data Set 6) and 35 min (Data Set 7), the total starting and handling times are 1,997.74 min and 2,386.89 min, respectively. The total starting time increases substantially when the trucks arrive late. A similar trend is observed when optimizing the second and third objective functions. The truck interarrival time affects the total starting and handling times of ITs

TABLE 2 Computational Results for Minimizing Different Objectives (Min)

	Minimizing Objective I			Minimizing Objective II			Minimizing Objective III		
Data Set	OF1	OF2	OF3	OF1	OF2	OF3	OF1	OF2	OF3
1	672.11	31,764	1,919.81	795.39	26,060	1,831.20	813.36	33,328	1,714.42
2	890.72	32,408	2,185.60	1,046.63	25,232	2,298.14	1,020.37	32,408	2,139.89
3	1,532.36	32,684	3,607.79	1,740.15	24,220	3,648.29	1,737.1	32,408	3,481.35
4	1,619.49	29,924	3,685.80	1,987.04	24,750	3,668.45	1,695.48	32,776	3,510.13
5	1,754.52	31,764	3,660.91	1,931.65	25,600	3,643.38	1,772.5	28,544	3,578.80
6	1,997.74	31,212	3,505.03	2,340.95	24,882	3,828.17	2,049.91	30,016	3,411.45
7	2,386.89	32,960	4,868.56	2,628.45	24,036	4,900.78	2,423.5	31,396	4,723.88

and the departure time of OTs. This is mainly because the service starting time of OTs partially depends on the starting time of serving ITs. It should be noted, however, that the difference in the departure time between Data Sets 3 and 6 is not obvious. This is because the departure time depends not only on the arrival time of trucks, but also on the handling time and travel time of pallets inside the facility. For interarrival times between 15 and 30 min, the total departure time of OTs does not vary substantially.

Comparison of Results

This section compares the performance of cross-docking operations under different objectives. Figure 2*a* shows the values of total starting and handling times of ITs when optimizing OF1 (total starting and handling times of ITs), OF2 (total weighted distance), and OF3 (total departure time of OTs). The figure shows that by minimizing OF2 and OF3, the value of OF1 increases in general, and the interarrival time of trucks increases as well. This increase, however, is not proportional, and in some instances a decrease in the OF1 value for higher interarrival times can be observed. Optimizing OF3 gives better values of OF1 compared with optimizing OF2. This is because minimizing the total departure of OTs directly affects the service time of ITs, whereas minimizing OF2 does not consider the performance of the starting and handling times of ITs.

Figure 2*b* shows the resulting values for the total weighted distance traveled by pallets inside the facility when optimizing OF1, OF2, and OF3. The values of total weighted travel distance from optimizing OF1 and OF3 are mostly between 30,000 and 34,000 ft, while the optimal value obtained from minimizing OF2 is around 25,000. This means that when minimizing OF1 and OF3, the results for OF2 are about 20% to 36% worse than when minimizing OF2.

Figure 2*c* shows the values of total departure time of all OTs when optimizing OF1, OF2, and OF3. The results indicate that both OF1 and OF2 produce good results for OF3. This is anticipated, as the departure time of OTs depends on the values of both OF1 and OF2, and, as discussed earlier, the starting and handling times of ITs almost determine the starting time for serving OTs. Therefore, it may be concluded—at least for a small-size cross-dock facility—that minimizing the total starting and handling times of ITs produces good results for the departure time of OTs.

Pareto Analysis of the Multiobjective Formulation

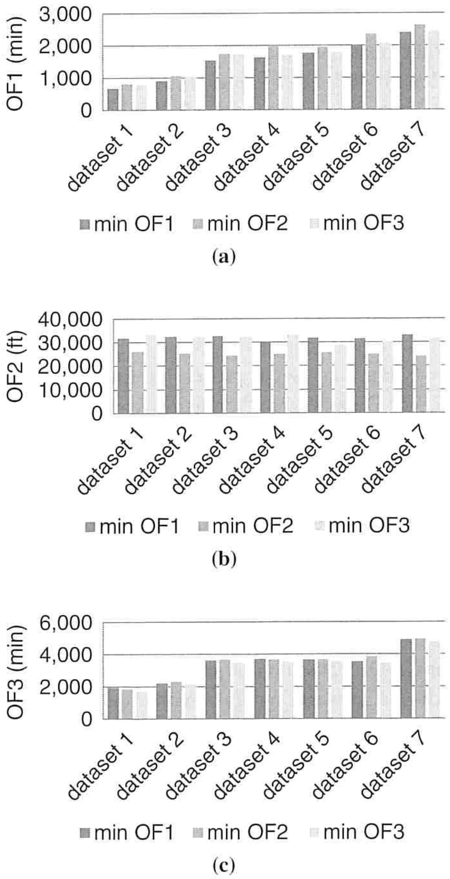
This section presents results of the multiobjective formulation of the problem. Most engineering optimization problems seek several objectives that often conflict with one another. These are known as multiobjective optimization problems and generally take the following mathematical form (*30*):

$$\min F(x) = [f_1(x), f_2(x), \ldots, f_N(x)] = [f_i(x)] \qquad i = 1, 2, \ldots, N$$

subject to

$$g_i(x) \le 0$$

$$h_i(x) = 0$$



(a)

(b)

(c)

FIGURE 2 Objective function values when minimizing OF1, OF2, and OF3 values: (*a*) values of OF1, (*b*) values of OF2, and (*c*) values of OF3.

where $f_1(x), f_2(x), \ldots, f_N(x)$ are the various objectives, and the inequality and equality constraints together define the feasible solution of the problem. There are numerous approaches to solving multiobjective problems, and most of them can be categorized into two groups. The first group aggregates the objectives quantitatively into a single objective, and the second one uses the concept of Pareto optimality to find the Pareto frontier or Pareto optimal set (*31–33*). The former approach requires the value of weights assigned to each objective function to be known. As these weights represent the view of decision makers, it is not always straightforward to estimate their value. This paper uses the concept of Pareto optimality to analyze a multiobjective problem. The solutions to a multiobjective optimization problem are a set of nondominated solutions; this set is usually known as a Pareto optimal set or Pareto front (*34*). The most intuitive approach to solving a multiobjective optimization problem is the weighted sum approach, which is used to find the Pareto optimal points:

$$U = \sum_{i=1}^{k} w_i f_i(x)$$

where w is a vector of weights. By changing the weights vector w, a set of points is obtained. To illustrate the performance of the objectives and apply the multiobjective analysis, Data Set 1 is used with different weights applied to different objective functions, combining them into a single objective function. Different weight combinations are used to generate different weighted objective functions, and each model is solved using the $k = 2$ approximation with the addition of Constraint 21. In total, 45 different weight combinations are applied, and the resulting models are solved. Not all the resulting points are Pareto front points. This is because of the application of this approximation method. If an exact solution method were used, all points satisfying $\Sigma_{i=1}^{3} w_i = 1$ and $w > 0$ should be Pareto front points (*35*).

TABLE 3 Pareto Front Points and Scored Pareto Front Solutions

	Weights			Value			
No.	OF1	OF2	OF3	OF1 (min)	OF2 (ft)	OF3 (min)	Score
2	0	1	0	795.39	26,060	2,298.14	0
4	0	0	1	813.36	33,328	1,714.42	0
7	0.1	0.9	0	672.11	29,464	1,947.06	11,869
8	0.1	0.3	0.6	673.49	31,764	1,732.59	34,504
9	0.1	0.1	0.8	687.21	32,776	1,724.03	5,471
16	0.2	0.5	0.3	672.11	31,948	1,750.41	28,098
45	1	0	0	672.11	31,764	1,919.81	0

Simple observation is conducted to obtain the seven Pareto front points from the 45 results, which are shown in Table 3. The rest of the points are dominated. In practice, a specific solution often needs to be selected from a set of Pareto optimal solutions. A procedure used to select one of the nondominated points is post-Pareto analysis. A post-Pareto analysis algorithm developed at the Center for Advanced Infrastructure and Transportation/Freight and Maritime Program at Rutgers University is used, and the results are shown in the last column of Table 3 (*30*). According to these results, solution number 8, with the highest score, is the best solution to sample Data Set 1. The weights of the first, second, and third objectives are 0.1, 0.3, and 0.6, respectively. The total starting and handling times of all ITs is 673.49 min; the total weighted distance traveled by all pallets inside the facility is 31,764 ft; and the total departure time of all OTs is 1,732.59 min. The detailed scheduling plan of ITs–OTs is shown in Figure 3. As a result of the restriction–approximation, each door serves two trucks; the starting time of serving each IT or OT is shown on the top of

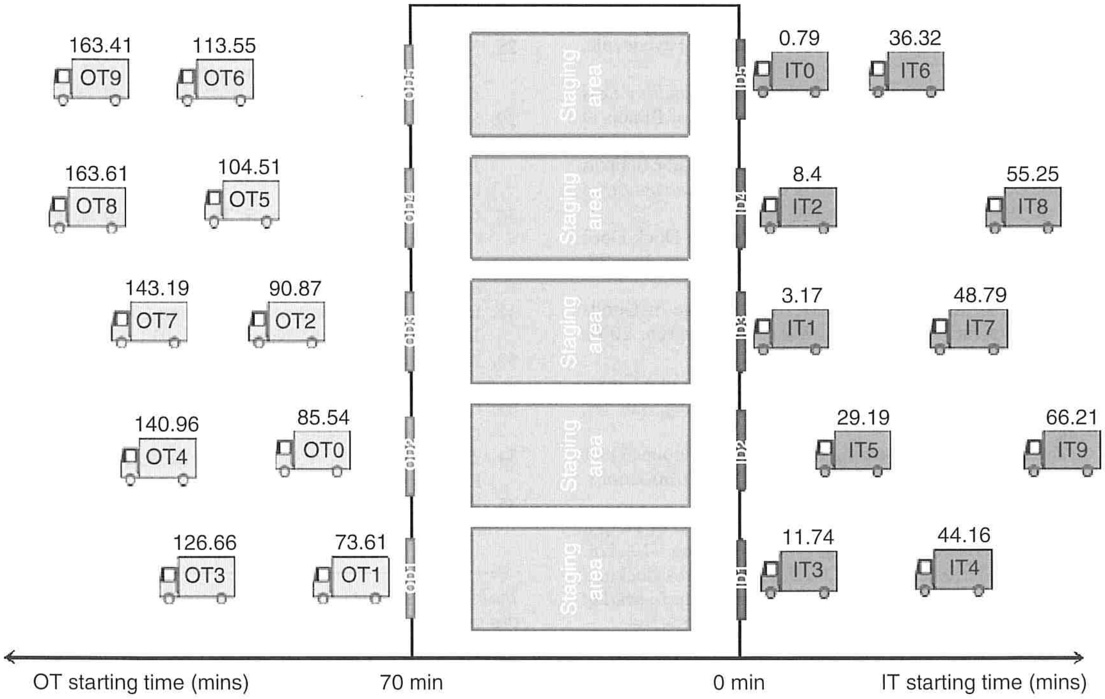


FIGURE 3 Scheduling results of ITs and OTs for example Data Set 1.

each truck. The sequence of serving ITs or OTs is also presented in the figure.

CONCLUSIONS

This paper deals with the scheduling of ITs and OTs at a cross-dock facility. A multiobjective MIP model is built that considers the three objectives of the problem. Because the problem is NP-hard, a restriction–approximation approach was developed to solve for each of the objectives. Numerical examples are provided along with an analysis of the computational results. Several observations can be made.

With this approximation approach, minimizing the departure time of OTs and the weighted travel distance gives a reasonable scheduling plan for trucks in terms of total starting and handling times of ITs. Moreover, neither the minimization of starting and handling times of ITs nor the minimization of total departure time of OTs gives a good scheduling plan in terms of minimizing the total weighted distance. At least for small-size cross-dock facilities, it is shown that the departure time of OTs mainly depends on the service starting and handling times of ITs. Finally, the multiobjective problem is solved, and a Pareto analysis is conducted using Data Set 1. The best resulting solution, which gives weight vectors of 0.1, 0.3, and 0.6 to the first, second, and third objectives, respectively, is picked from the Pareto optimal solutions by applying post-Pareto analysis.

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Impact of Truck Arrival Information on System Efficiency at Container Terminals

Wenjuan Zhao and Anne V. Goodchild

This paper quantifies the benefits to drayage trucks and container terminals from a data-sharing strategy designed to improve operations at the drayage truck–container terminal interface. This paper proposes a simple rule for using truck information to reduce container rehandling work and suggests a method for evaluating yard crane productivity and truck transaction time. Various scenarios with different levels of information quality are considered to explore how information quality affects system efficiency (i.e., truck wait time and yard crane productivity). Different block configurations and truck arrival rates are also investigated to evaluate the effectiveness of truck information under various system configurations. The research demonstrates that a small amount of truck information can significantly improve crane productivity and reduce truck delay, especially for those terminals operating near capacity or using intensive container stacking, and that complete truck arrival sequence information is not necessary for system improvement.

Marine container terminals are important intermodal interfaces between marine and surface transportation. Efficient operation of container terminals can improve port productivity, reduce drayage truck wait time, and reduce the social cost of the intermodal system. Recently, container terminals on the West Coast of the United States have improved operations by automating gate transactions, establishing gate appointment systems, and extending gate hours. Some of those measures have been effective; others have not. For example, some gate appointment systems have been reported to have not reduced truck queuing or transaction times (*1*).

This research addresses the problem of whether and how truck arrival information can be used to improve the drayage truck–container terminal interface, using a mechanism that is aligned with both the container terminal and drayage trucks' incentive schemes. This research also considers how to use truck information to improve import container retrieval operation. The objective of this research is to identify the information required to achieve a significant improvement in truck transaction time and terminal handling efficiency and evaluate the impact of different yard configurations on the effectiveness of this truck information.

LITERATURE REVIEW

There is a wide body of literature that considers improvements to marine terminal operations; only research closely related to the present study is described here. Holguín-Veras and Walton studied improving the level of service for containers with a higher priority at container terminals by implementing priority systems (*2*). They considered a group of priority systems, including locating high-priority containers on special hatches, storing them on chassis, or using automatic equipment identification devices at gates and assessed the impacts on different users using a computer simulation. They concluded that the implementation of priority service significantly improves the performance of high-priority containers without overly penalizing the level of service for low-priority containers or the terminal's operating costs.

Some researchers have studied how to reduce truck transaction time at a container yard by better utilizing the current system or improving operational methods. Huynh and Walton studied regulating the number of trucks that can enter the terminal to make the gate appointment system effective (*3*). They proposed a methodology that is a combination of mathematical formulations and computer simulations to determine the maximum number of trucks allowed to enter the terminal while maintaining a target truck transaction time. Kim et al. studied sequencing trucks for container transfer operations to minimize truck delay at the container yard (*4*). A due time for transfer service is assumed for each truck, and the delay of a truck beyond the due time results in a penalty cost. A dynamic programming model was developed to minimize the total delay cost, and a learning-based method for deriving decision rules was suggested to solve the model. Kim and Kim also studied optimizing the size of the terminal storage space and number of yard cranes for handling import containers and developed an analytical cost model that addresses terminal space cost, the investment and operating cost of yard cranes, and the waiting cost of outside trucks (*5*). In that model, truck cost was estimated based on truck transaction time, and transaction time was evaluated by formulating the container transfer operation for trucks as an M/G/1 queuing model.

The most closely related paper was written by Jones and Walton (*6*). They studied whether and how more accurate and timely information about the departure times of containers can be used to more efficiently and effectively manage import containers in stacked storage. They developed an event-based simulation model capturing the interactions among a port's various subsystems to evaluate the impact of using this departure information on the number of container rehandles, ship turnaround time, and average cost per container moved through the port. Their study assumes that the import container departure time has been acquired by the terminal operator prior to the ship unloading, and they used this information to determine the container stacking sequence on the yard during the ship unloading process. With the same overall intent of reducing

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rehandling activity, Jones and Walton also studied a different component of terminal operations (unloading containers to stacks) and solved a different mathematical problem. This paper assumes that truck arrival time is obtained after import containers have been stored in the yard, mimicking the practice of having real-time rather than strategic information.

Zhao and Goodchild addressed the problem of using truck arrival information to reduce import container rehandling work at the terminal (*7*). The research presented in this paper develops that work for import containers, identifying the improvements in truck transaction time and yard crane productivity from the same strategy proposed previously, which uses truck arrival information to reduce container rehandling work (*7*).

The paper is organized as follows. The first section introduces research assumptions, basic scenarios, and operation rules for using truck information. The next sections describe the method used to evaluate crane productivity and truck transaction time and provide the results of numerical experiments. Conclusions are then presented.

ANALYSIS FRAMEWORK

Assumptions and Scenario Definitions

This study considers the retrieval of import containers by the yard crane within a container block to serve drayage trucks (Figure 1). Several assumptions are made:

1. The yard crane serves the drayage trucks using the first-in-first-out (FIFO) rule;
2. Rehandled containers are relocated to a slot within the same bay;
3. No additional containers are added to the block during the container pick-up process;
4. Truck arrivals can be modeled by a Poisson process;
5. The location of the container requested is randomly distributed;
6. The location of each container in the block is known in advance and tracked throughout the pickup process; and
7. Truck arrival information includes the container to be retrieved.

Under the second assumption, container bays are independent of each other; thus, the analysis for container rehandling work is performed for one bay by one crane, and the result is the same for any bay within the block. This research on the operation of one yard crane within a container block can be extended to the whole container yard, with multiple yard cranes given identical assumptions for each crane. In that situation, the container yard can be segregated into multiple subareas, with each subarea assigned to one yard crane and with each crane modeled as an independent system. The third assumption posits that containers unloaded from arriving ships are not stored on top of existing containers unloaded from ships that had previously arrived. Mixing containers with different arrival times in such a way causes excessive container rehandling work and should be avoided. If such a mixing strategy exists, this research would underestimate the number of rehandles, and the actual benefit to the terminal and trucks would be larger than the estimate presented in this paper.

Truck information is considered for container retrieval within the same bay. Currently, terminals have limited knowledge of truck arrival sequences. For those terminals in which a gate appointment system is implemented and appointments are met, the arrival time window of trucks is available and could be translated into arrival groups. If a much narrower appointment time window were adopted or if the terminal tracked the real-time location of each truck and could estimate arrival times, a more complete truck arrival sequence would be available. On the basis of the amount of known truck information

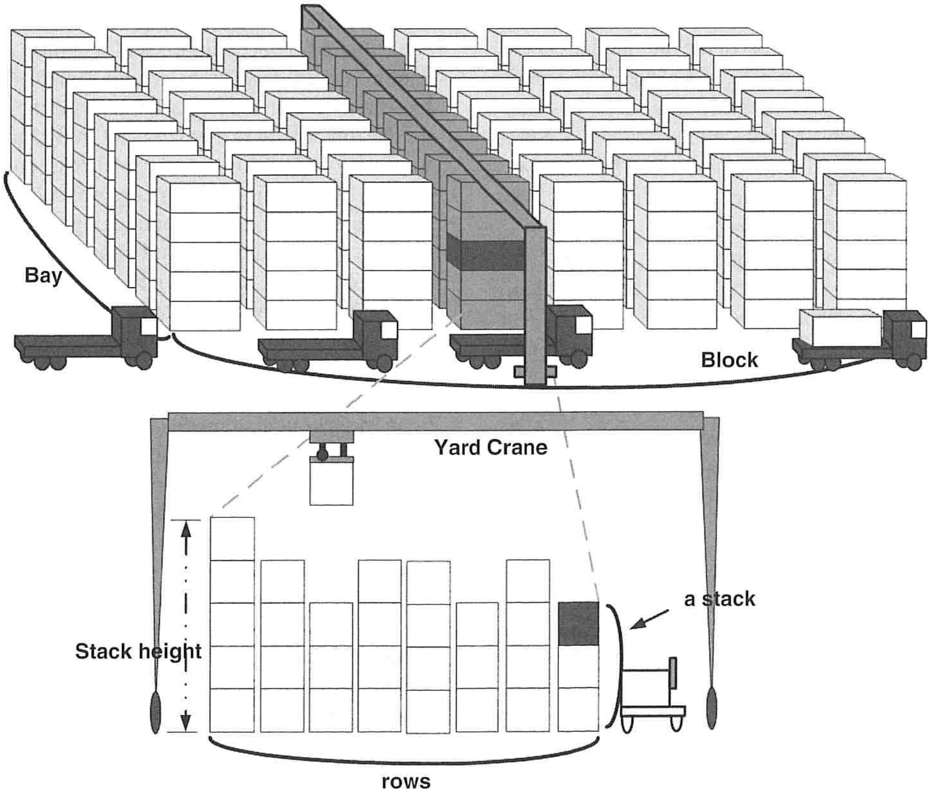

FIGURE 1 Container block configuration and terminology.

TABLE 1 Scenario Definitions

Scenario	Definition
No truck information	No truck information is available.
Static group information	The terminal knows in which of several groups a truck will arrive, but not the exact order of truck arrivals within any group. For example, trucks can be assigned to one of two groups, A or B. The terminal knows which trucks are in Group A and which trucks are in Group B, and that all trucks in Group A will arrive before any truck in Group B. But the exact arrival sequence of trucks within Group A or B is not available. "Static" means information is provided before any truck arrives, and is not updated over time.
Static partial sequence	The terminal knows in which of several groups a truck will arrive, and the exact order of truck arrivals for the first group. Information is not updated over time.
Dynamic group information	The terminal knows in which of several groups a truck will arrive, and the group information is updated over time. Every time all the trucks in the first group are exhausted, the terminal receives information about the arrival group of the next *N* trucks, where *N* is the number of trucks in the original first group. Figure 2*a* is provided as an example. After the two trucks in group A have been served, information about a new arrival group of the next two trucks becomes available, which emerges from Group B and forms a new Group A, with its size equal to the old Group A. The updating process continues until no trucks remain in Group B.
Scenario with dynamic partial sequence	The terminal knows in which of several groups a truck will arrive, and the arrival sequence of the first group. After a truck in the first group is served, information about the first truck within the next group becomes available, and this truck joins the first group. Take Figure 2*b* as an example. After Truck 1 has been served, information about the first truck in Group B becomes available, and Truck 3 enters Group A. The size of Group B shrinks. The updating process continues until no trucks remain in Group B.
Scenario with complete sequence	The complete sequence of truck arrivals is known.

and whether the information is static or updated in real time, six scenarios are defined to represent situations with various information qualities (see Table 1 and Figure 2). A more general definition of scenarios with regard to truck information quality and a detailed explanation is presented in previous work by the authors (*7*).

Truck arrival information is useful in reducing number of container rehandles by carefully determining the storage location of rehandled containers. The next subsection introduces the rules of container relocation for this strategy. This information is contained in the authors' previous work (*7*).

Rules for Using Truck Information

Without truck arrival information, rehandled containers can be relocated to the nearest available stack. This strategy minimizes the travel distance of the yard crane and is used widely in container terminals. This strategy will be referred to as the "nearest relocation rule" and applied to the scenario with no truck information for container relocation.

The revised difference heuristic is applied to all the other scenarios with some truck information. This rule is extended from Aydin's work (*8*). Aydin proposed the difference heuristic algorithm to address the container relocation problem given a complete truck arrival sequence; this algorithm is improved to address the problem of incomplete truck information and is referred to as the "revised difference heuristic." This algorithm requires each container's retrieval order number as input. The retrieval order number can be obtained by relating the truck arrival sequence (or group) to the container of interest. Given truck arrival information, the revised difference heuristic can be applied to determine the best storage location of the rehandled container (i.e., the location that incurs fewest future

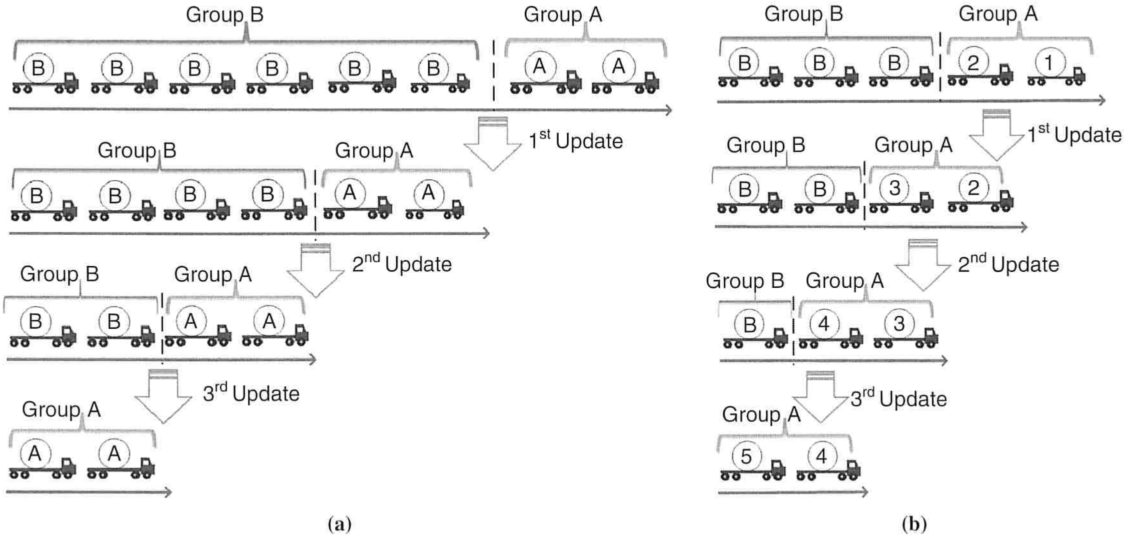

FIGURE 2 Information updating rule for dynamic scenarios: (*a*) dynamic group information and (*b*) dynamic partial sequence.

rehandles). The revised difference heuristic is described below, with X denoting the order number of the container to be rehandled.

Revised Difference Heuristic

Step 1. When relocating container X, search for a stack with container Y whose order number is the smallest in its stack and yet still bigger than X. In this way, no additional rehandles will be necessary for container X. If multiple stacks satisfy this condition, then the stack containing the smallest Y is chosen. If such a stack does not exist, go to step 2.

Step 2. Search for a stack in which the container with the smallest order number is the same as X. If multiple stacks satisfy this condition, then randomly select one. If such a stack does not exist, go to step 3.

Step 3. Search for a stack with container Z that is accessible by the crane and has an order number smaller than X. If multiple stacks are found, choose the one with largest Z to minimize the difference between X and Z. If such a stack does not exist, go to step 4.

Step 4. Search for a stack with the goal of minimizing the difference in order number between its top container and X.

Decisions are made sequentially regarding relocations using the revised difference heuristic, from the top container on the target stack (the stack in which the requested container is located) to the one just above the required container.

RESEARCH METHODOLOGY TO EVALUATE CRANE PRODUCTIVITY AND TRUCK TRANSACTION TIME

In this section, the method used to estimate crane service time is first described, and a queuing model is presented to evaluate truck transaction time. Crane productivity is the reciprocal of the average crane service time. Truck transaction time depends on the interarrival time of trucks and the service time of the yard crane.

Crane Service Time Estimation

Crane service time includes the travel time between yard bays, the rehandling time required to move containers on top of the target container, and the handling time for the target container. One container block filled with 40-ft standard containers is considered, and the following notation is used to estimate the crane service time (see Figure 1 for the definition of bays, blocks, stack, and row).

Other terms are defined as follows:

c = number of bays in the block;
a = number of stacks in each bay;
b = initial number of containers in each stack;
h_1 = horizontal distance traveled by the trolley to relocate the rehandled container;
d_1 = vertical distance traveled by the trolley to pick up the rehandled container;
d_2 = vertical distance traveled by the trolley to drop the rehandled container;
h_2 = horizontal distance traveled by the trolley to handle the required container;
d_3 = vertical distance traveled by the trolley to pick up the required container;
d_4 = vertical distance traveled by the trolley to drop the required container on the drayage truck;
v_t = average travel speed of the crane across the yard bays;
v_f = average hoist speed of the trolley when moving a container;
v_e = average hoist speed of the trolley when not moving a container;
v_h = average horizontal travel speed of the trolley;
R = number of rehandles to serve one truck;
T_t = crane travel time between yard bays;
T_r = rehandling time;
T_d = required container handling time; and
T_o = time needed to perform one container rehandle.

Crane Travel Time Estimation (T_t)

Under the assumption that trucks are served following the FIFO rule and that the requested container location is randomly distributed, the expected distance between two random retrievals is $c/3$, and the variance can be derived as $c^2/18$. Thus, the mean and variance of the travel time across container bays to pick up one import container are as follows:

$$E(T_t) = \frac{c}{(3v_t)} \tag{1}$$

$$V(T_t) = \frac{c^2}{(18v_t^2)} \tag{2}$$

Crane Rehandling Time Estimation (T_r)

The number of rehandles and the time needed to rehandle one container are assumed to be independent. Consequently, the expected rehandling time can be calculated as the product of the expected number of rehandles and the expected time to rehandle one container.

Estimation of Time to Rehandle One Container (T_o) One rehandle is defined as a complete cycle: the trolley reaches the container to be rehandled, moves it to another stack, and returns it to the original stack. The trolley first travels vertically and horizontally with the container and then travels back empty. An upper bound for the cycle time can be derived by assuming the horizontal movement and vertical movement are carried separately. As illustrated in Figure 3,

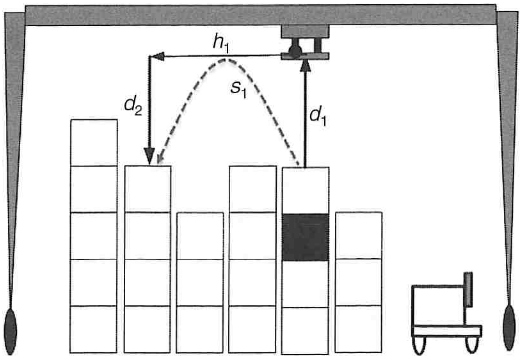

FIGURE 3 Trolley movements in one rehandle cycle.

the trolley travels along the path $d_1 \rightarrow h_1 \rightarrow d_2$. The upper bound can therefore be estimated as

$$T_o^u = \frac{d_1}{v_f} + \frac{d_2}{v_f} + 2 \cdot \frac{h_1}{v_h} + \frac{d_2}{v_e} + \frac{d_1}{v_e} \qquad (3)$$

A lower bound for the cycle time can be derived by assuming that the horizontal movement and vertical movements are carried simultaneously. This is also illustrated in Figure 3, in which the trolley travels along trajectory s_1. The lower bound can be estimated as

$$T_o^l = \max\left(\frac{d_1}{v_f} + \frac{d_2}{v_f}, \frac{h_1}{v_h}\right) + \max\left(\frac{d_2}{v_e} + \frac{d_1}{v_e}, \frac{h_1}{v_h}\right) \qquad (4)$$

The average of the upper and lower bounds is used to estimate the expected time to rehandle one container. Because the variance of T_o is small, its impact on the model outcome can be neglected, and the variance of T_o is assumed to be zero.

Estimation of Number of Rehandles (*R*) The expectation and variance for the number of rehandles can be estimated based on the probability distribution of the number of container rehandles. A computer-based simulation is developed to model the container pickup operation and is used to derive the probability distribution of the number of rehandles for one import container pickup under different scenarios. The computer system simulates the container retrieval process for a bay of containers under specified rules of container relocation and keeps track of the number of rehandles performed and the horizontal distance traveled by the trolley. The program is able to evaluate the amount of rehandling work under various truck information qualities and bay configurations. A detailed description of the computer simulation can be found in Zhao and Goodchild (*7*).

The expectation and variance of rehandling time can be calculated as follows:

$$E(T_r) = E(T_o) \cdot E(R) \qquad (5)$$

$$V(T_r) = E(T_o)^2 \cdot V(R) \qquad (6)$$

Crane Handling Time Estimation (T_d)

One handle for an inbound container is defined as a cycle that starts with the trolley above the truck lane, moves to reach the required container, travels back to drop it on a drayage truck, and returns to its initial position. The expected handling time for one container can be estimated by deriving an upper bound and a lower bound for handling time; the variance is assumed to be zero.

The upper bound and lower bound of T_d is estimated following the same logic used to evaluate T_o. The upper bound of T_d can be written in the same format as Equation 3, but replacing d_1, d_2, h_1 with d_3, d_4, h_2; the lower bound of T_d can be expressed as

$$T_d^l = \max\left(\frac{d_3}{v_f}, \frac{h_2}{v_h}\right) + \max\left(\frac{d_3}{v_e} + \frac{d_4}{v_e}, \frac{h_2}{v_h}\right) + \frac{d_4}{v_e} \qquad (7)$$

Estimated Crane Service Time and Crane Productivity (T_c)

Because the handling time for an import container, the rehandling time, and the travel time can all be assumed to be independent of each other, the expectation and variance of crane service time can be estimated as

$$E(T_c) = E(T_t) + E(T_r) + E(T_d) \qquad (8)$$

$$V(T_c) = V(T_t) + V(T_r) \qquad (9)$$

Crane productivity can be estimated as the reciprocal of average crane service time.

Truck Transaction Time Estimation

Assume truck arrivals follow a Poisson process with the arrival rate λ. For a yard crane working within a block of inbound containers, the container retrieval operation can be modeled as an M/G/1 queuing system, with the yard crane being the single server and the arriving trucks as customers (Figure 1). The traffic density is

$$\rho = \lambda \cdot E(T_c) \qquad (10)$$

Expression 11 can be used to calculate the expected truck transaction time (*9*):

$$E(W) = E(T_c) + \frac{\lambda \cdot V(T_c) + \rho \cdot E(T_c)}{2(1-\rho)} \qquad (11)$$

NUMERICAL EXPERIMENTS

This section presents the estimated improvements in crane productivity and truck transaction time if a terminal utilizes truck arrival information to reduce rehandling work. The impact of various information qualities, truck arrival rates, and block configurations on drayage truck–yard crane system performance was evaluated to identify the effectiveness of truck information under different system configurations. The parameter values of the yard crane are listed in Table 2 and were used for the numerical experiments.

For any given bay configuration, the parameter values for d_1, d_2, d_3 are calculated by subtracting the average stack height ($b/2$) from the crane lifting height, and d_4 is calculated by subtracting the truck chassis height from the crane lifting height. Here, 1.450 m is used as the chassis height (*11*). For a scenario without truck information, h_1 is estimated based on the simulation result regarding the average horizontal distance traveled by a trolley for one rehandle; for all other scenarios, h_1 is estimated as being one-half of the block width

TABLE 2 Specifications for Rubber-Tired Gantry Crane (*10*)

Parameter	Value
Gantry travel speed (v_t)	115 m/min
Hoist speed with full load (v_f)	30 m/min
Hoist speed with empty load (v_e)	63 m/min
Trolley travel speed (v_h)	70 m/min
Crane lifting height	12.34 m for two-container-high block 15.24 m for three-container-high block 18.14 m for four-container-high block 21.04 m for five-container-high block 23.94 m for six-container-high block

($a/2$). h_2 is also estimated as being one-half of the block width ($a/2$). The container dimension is the standard 40 ft.

Performance Analysis Under Various Information Qualities

A block with $a = 6$, $b = 5$, $c = 40$, and $\lambda = 6$/h is considered. Arrival trucks retrieving containers from the same bay are assigned into two groups, and the impact of truck group size on the performance of the yard crane service system is shown in Figures 4 and 5.

Figures 4 and 5 demonstrate that truck information can generate significant benefit for both the marine terminal and trucks. Notice the similarities between the two figures, indicating that the change in truck group sizes has similar impacts on both crane productivity and truck transaction time. Two other observations can be made from Figures 4 and 5.

First, given static information, the value of truck group information is maximized when the sizes of the two groups are equal. The value of partial sequence information grows steadily with the length of the sequence.

Second, updating information in real time can lower the requirement for information quality. For the scenario with dynamic group information, the peak benefit is realized at a much smaller first group; for the scenario with dynamic partial sequence information, significant benefit is achieved from knowing one-sixth of the total sequence, and little additional value is generated from a longer sequence. Therefore, a complete sequence is not required to significantly improve system performance if real-time information is available.

Performance Analysis Under Various Truck Arrival Rates

Consider a block with $a = 6$, $b = 5$, and $c = 40$. It is assumed that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for one-third of the total number of arriving trucks. The change in truck arrival rate has no impact on crane service time but affects the truck waiting time within the system. The truck transaction time is evaluated under a range of arrival rates from 4/h to 10/h, and the result is presented in Figure 6.

Figure 6 shows that truck time savings resulting from any level of information quality grows exponentially with truck arrival rates. Especially when the truck arrival rate is approaching the crane service rate, a 35% reduction in transaction time can be realized from knowing truck arrival groups only. Therefore, the truck information is more valuable for the system operating near capacity, and a small amount of truck information can be very effective in reducing truck delay.

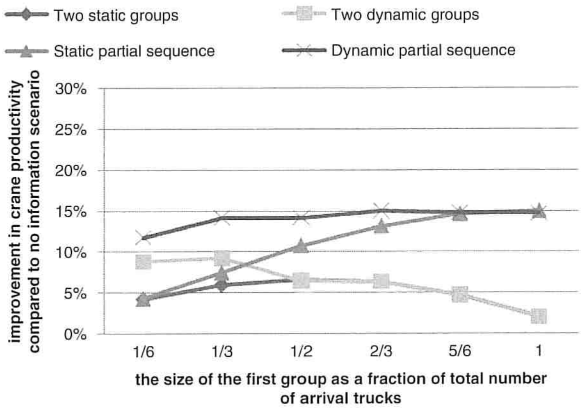

FIGURE 4 Improvements in crane productivity under various first truck arrival group sizes.

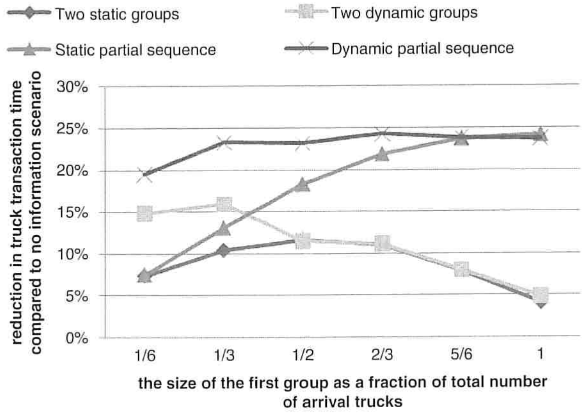

FIGURE 5 Percentage savings in truck transaction time under various first truck arrival group sizes.

Figure 6 also demonstrates the consistent effect of truck information quality on truck transaction time under different truck arrival rates. In general, having information for two static truck groups can generate almost one-half of the truck time savings achieved from having a complete sequence; having dynamic group information is more valuable than knowing one-third of the truck arrival sequence and can result in an additional 2% to 4% in time savings. Dynamic partial sequence information can provide almost the same amount of benefit as complete sequence information. Therefore, better information quality can further reduce truck transaction time, but the complete sequence is not required.

Performance Analysis Under Different Block Configurations

Consider a block with 1,200 containers, $\lambda = 6$/h, and a block with $a = 6$, $b = 5$, and $c = 40$ as the base configuration. It is assumed that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for one-third of the total number of arrival trucks.

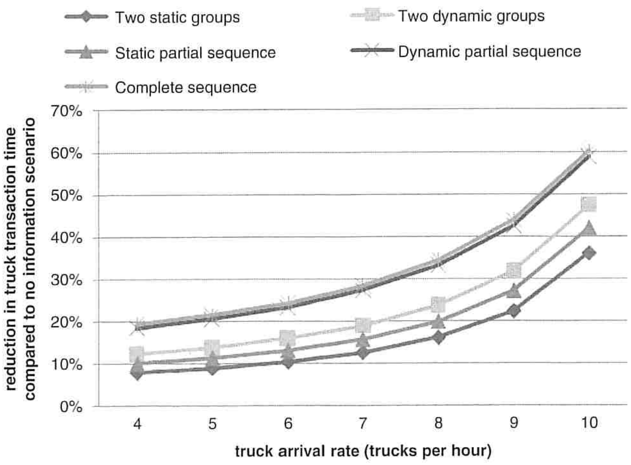

FIGURE 6 Percentage savings in truck transaction time under various arrival rates.

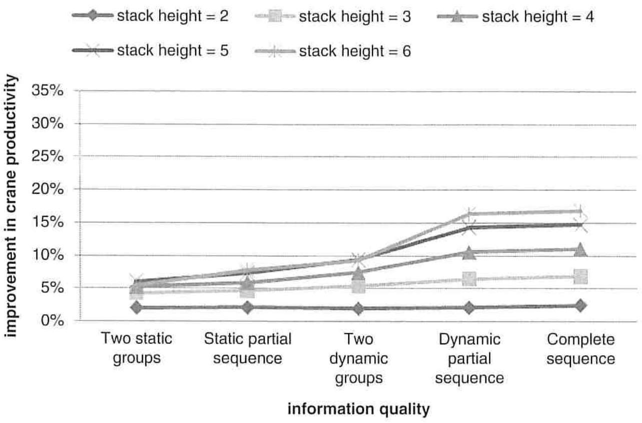

FIGURE 7 Crane productivity under various configurations of stack height and bay numbers.

Figures 7 and 8 illustrate the performance of the yard crane service system under various block configurations with six rows ($a = 6$). Different combinations of stack height and bay numbers have a similar effect on crane productivity and truck transaction time. Two observations can be made. First, given the same level of information quality, the truck information generates a bigger benefit for the block configuration with higher stacks and fewer bays. Second, better information quality can bring additional benefit for the block configuration with higher stacks and fewer bays; however, its value decreases with the stack height. Static group information is sufficient for system improvement for the block configuration with shorter stacks and more bays.

Figures 9 and 10 illustrate system performance under the block configuration with an initial stack height of five ($b = 5$). Again, different combinations of the number of rows and bays have a similar impact on both crane productivity and truck transaction time. Two observations can be made. First, given the same level of information quality, the information provides larger benefit for the block configuration with more rows and fewer bays. Second, the magnitude of benefit grows steadily with better information quality for any combination of row numbers and bay numbers. A comparison between Figures 7 and 8 and Figures 9 and 10 shows that stack height has more impact on the effectiveness of utilizing arrival information than other block configuration factors.

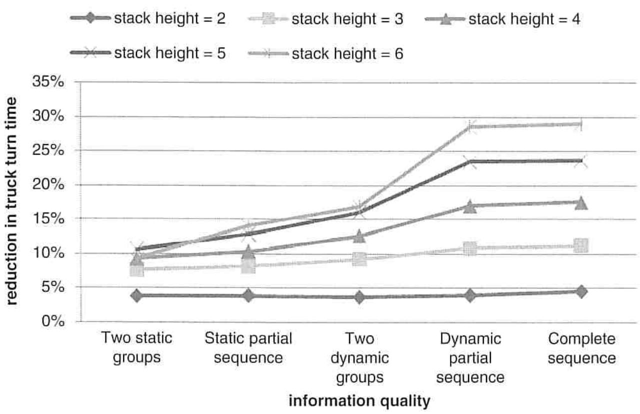

FIGURE 8 Truck transaction time under various configurations of stack height and bay numbers.

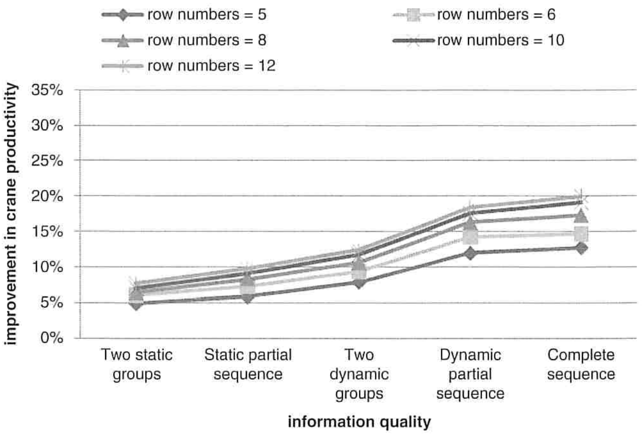

FIGURE 9 Crane productivity under various configurations of row numbers and bay numbers.

CONCLUSION

This paper presents the impact of truck arrival information on the drayage truck–yard crane system. A simple rule for using truck information is adopted to reduce container rehandles, and an M/G/1 queuing model is used to model the interaction between the yard crane and arriving trucks. The model is designed to evaluate how strategic factors such as the level of truck information quality and container block design affect system improvements achieved by utilizing truck information. These results can identify terminals likely to experience significant benefits and can inform the design of a data-sharing system. For very detailed estimates of improvements at a particular terminal, a microsimulation model should be developed that captures the unique terminal configuration, flow rates, and processing times.

These research results demonstrate that truck arrival information is effective for improving crane productivity and reducing truck transaction time. Group information alone can effectively improve system performance; updating information in real time lowers the information requirement and provides significant benefit with a small amount of information. In fact, real-time partial sequence information can generate about the same benefit as the complete arrival sequence, even if the partial sequence is for just one-third of the total number of trucks. Complete sequence information is not required to maximize the benefit.

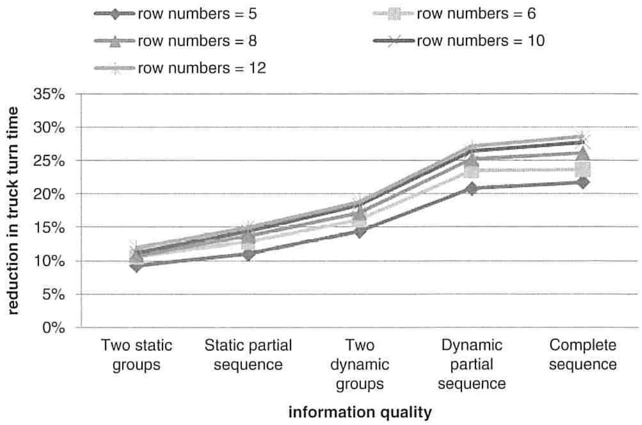

FIGURE 10 Reduction in truck turn time under various configurations of row numbers and bay numbers.

The results also shed light on the relationship between benefits and block configuration. For those terminals with limited yard space and high stacking, truck information is more effective for system improvement, and better information quality is useful for further enhancing the magnitude of benefit. For those terminals with more yard space, the static truck group information can moderately improve system efficiency. Truck information is especially valuable for the system operating near capacity.

The work illustrates that utilizing truck information can benefit both the marine terminal through reduced rehandling work and drayage trucks through reduced turn times. These benefits are naturally aligned with each party's interests. Having any amount of information is useful for improving system performance. Truck information could be obtained in a variety of ways, including using existing gate appointment systems, which could provide some information about truck arrival time windows, or receiving phone calls from approaching trucks. Utilizing currently available information such as this does not require much effort or cost; however, it does require cooperation between the terminal and trucking operations.

ACKNOWLEDGMENT

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The Intermodal Freight Terminal Design and Operations Committee peer-reviewed this paper.

Air Pollution Impacts of Shifting Freight from Truck to Rail at California's San Pedro Bay Ports

Soyoung (Iris) You, Gunwoo Lee, Stephen G. Ritchie, Jean-Daniel Saphores, Mana Sangkapichai, and Roberto Ayala

Escalating concerns about air quality in southern California have led authorities at the Ports of Los Angeles and Long Beach, also known as the San Pedro Bay Ports (SPBP), to adopt a number of measures designed to mitigate emissions. One way to do this is to shift some of the containers currently transported by drayage trucks to trains. This alternative is attractive because it would decrease congestion and air pollution on the area's main freeways (I-710 and I-110) and the arterials that serve the SPBP. In addition, it would increase road safety along the busy Alameda freight corridor between the SPBP and downtown Los Angeles. One drawback would be an increase in pollutant emissions from train operations in the Alameda corridor; however, trains tend to pollute less than trucks per ton-mile, and new federal regulations are tightening the emissions standards for diesel locomotives. The goal of this paper is to quantify the net impact of such a modal shift on the emission of particulate matter (PM) and nitrogen oxides (NO_X), the two air pollutants of most concern in the SPBP area. This analysis relies on microscopic simulation to capture emissions resulting from stop-and-go traffic on the freeways serving the SPBP. It was found that emissions of both NO_X and particles less than 2.5 μm in diameter ($PM_{2.5}$) can be significantly reduced by switching from drayage trucks to trains. This finding suggests that a modal shift should be encouraged, especially if there is unused train capacity and if the shift does not conflict with the shippers' interests.

Escalating concerns about air quality in southern California have led the authorities of the Ports of Los Angeles and Long Beach, also known as the San Pedro Bay Ports (SPBP), to adopt a number of measures intended to mitigate emissions. Their goal was to improve the environmental performance of the SPBP complex to facilitate its continued expansion.

A number of state and regional agencies have been involved in this multiyear effort, including the California Air Resources Board (CARB) and the Southern California Association of Governments (SCAG). Clean-up plans, which cover a time horizon that extends until 2020, target emissions from ships, commercial harbor craft, locomotives, and trucks. In particular, truck emission reduction strategies include modal shifts from trucks to rail (*1–3*). This approach is expected to mitigate multiple environmental impacts associated with the movement of goods. First, it should reduce the volume of heavy truck traffic that currently contributes to local congestion and air pollution on major routes serving the SPBP complex, especially I-710 and I-110 and the connected freeways (SR-47, I-405, SR-91, I-105, and I-5). Second, it will likely improve road safety along this busy freight corridor. And although shifting port traffic from drayage trucks to trains will likely increase pollution from train operations in the area, the net effect should still be positive because trains tend to be cleaner than trucks per ton-mile, and the U.S. Environmental Protection Agency (EPA) is tightening emissions standards for diesel locomotives (*4–6*).

The *San Pedro Bay Ports Clean Air Action Plan* emphasizes the development of on-dock rail (where containers are transferred directly from a ship to a train), and statistics show that the share of on-dock use has gradually increased over time, from 15.9% in 2003 to 24.1% in 2006 (*7*). According to the *San Pedro Bay Ports Rail Study Update,* each on-dock train can eliminate up to 750 truck trips, which in turn reduces drayage truck pollution and improves road safety. In particular, this reduces the emission of particulate matter (PM), but it also affects the emission of other criteria pollutants (*6*). However, the development of on-dock rail alone will not eliminate the need for near-dock and off-dock trips and related truck trips on local freeways and arterials.

Efforts by the SPBP complex to improve air quality appear to be bearing fruit. Indeed, a comparison of the 2007 and 2005 emissions inventories for the Port of Long Beach shows that emission of nitrogen oxides (NO_X), sulfur oxides (SO_X), and hydrocarbons (HC) went down by 1%, 87%, and 17%, respectively, although emission of PM and carbon monoxide (CO) increased by 7% (*8, 9*). This change is still remarkable considering the 9% increase in total 20-ft equivalent (TEU) throughput that took place over that period at the ports, which was accompanied by a 3% increase in total vehicle miles traveled (VMT) and a 43% jump in the tonnage handled by on-dock rail.

A few studies have analyzed the potential impacts of shifting container traffic from trucks to train, but they relied on planning models that are unable to capture the impacts on emissions of road congestion, as they take into account only average speed and VMT. For example, Fischer et al. (*10*) proposed using macroscopic emissions analysis to evaluate truck trip reduction strategies, including expanded on-dock rail facilities, a new near-dock rail intermodal terminal, and an inland rail shuttle service. More recently, using TransCAD and the California Environmental Protection Agency's EMission FACtors for 2002 (EMFAC2002),

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Park et al. found that shifting 10% of the heavy-duty truck traffic to trains for the year 2000 reduced NO$_X$ emissions by 35.8 kg/h and cut PM emissions by 0.6 kg/h; shifting 20% roughly doubled these amounts (*11*).

The objective of this paper is to present a more sophisticated analysis based on microscopic simulation of the traffic and air quality impacts of shifting some container traffic from drayage trucks to rail via on-dock services. Several authors, including Nesamani et al., have shown that microscopic simulation (in this case, using Paramics) provides better estimates of air pollution emissions because it explicitly models accelerations and decelerations, lane changing, and merging and diverging, which are especially important in stop-and-go traffic (*12*). In contrast, static planning models ignore individual vehicle behavior, which underestimates pollutant emissions and does not account for link capacity. Excessive traffic volumes are thus assigned to specific links in congested conditions, resulting in emission overestimates. As a result, estimates of emissions based on static planning models suffer from significant biases in different traffic conditions.

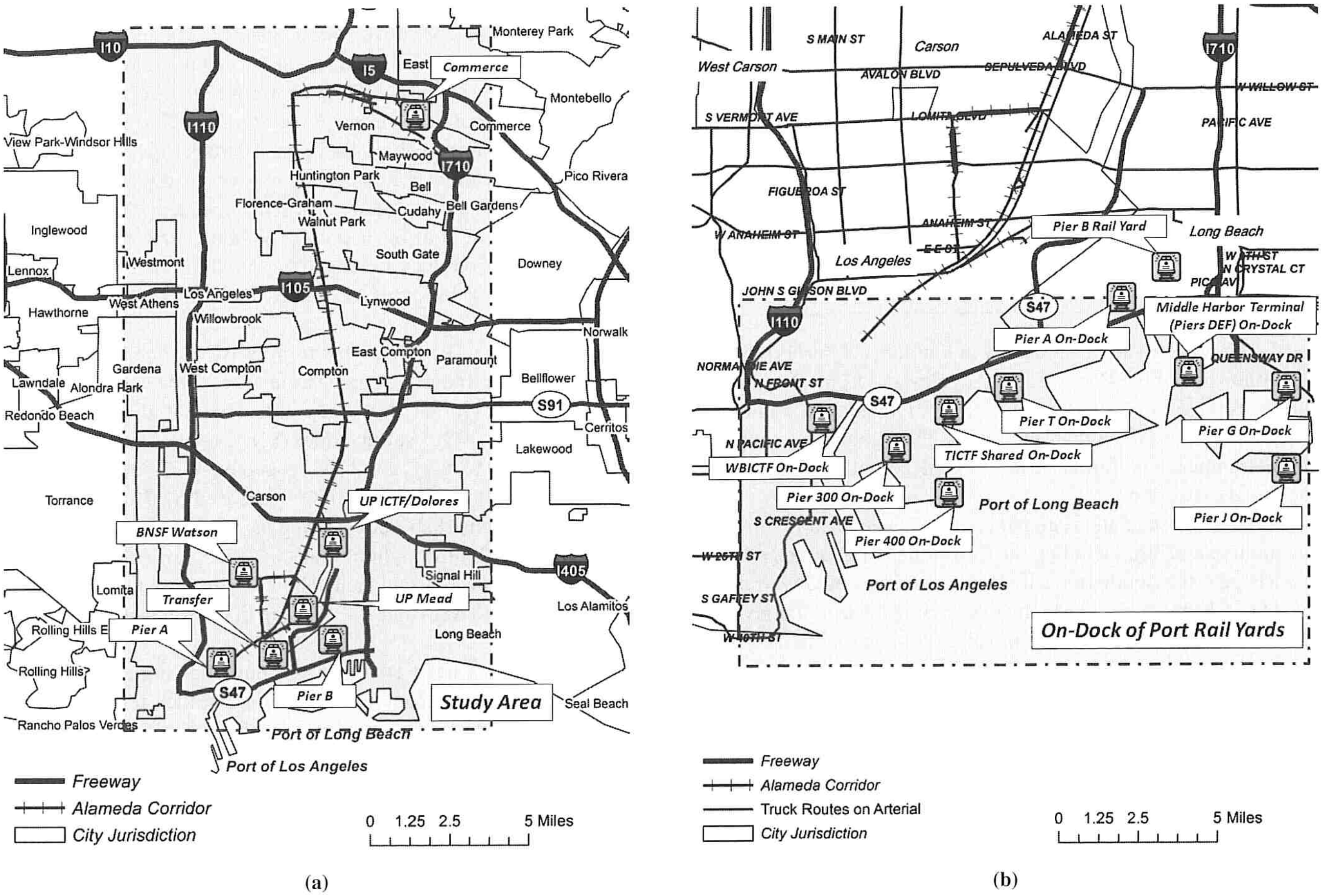
The study area addressed in this paper is shown on the left panel of Figure 1. It includes the main freeways that serve the SPBP complex along with the Alameda corridor (a key rail link to the ports), and a number of rail yards. For microscopic simulation, this study relies on TransModeler and focuses on 2005 as the base year (*13*). The results quantify emissions gains and losses from drayage trucks and trains, with an overall systemwide reduction in emissions of NO$_X$ (1.0%) and PM (0.4%).

This paper is organized as follows. First, background information about the freight corridor linked to the SPBP complex is introduced, and an overview of the methodological framework is provided. The results of the analyses for both truck and train emission estimates are summarized. Emission trade-offs resulting from shifting container traffic from trucks to trains is discussed, and concluding remarks and suggestions for future work are presented.

STUDY SITE

The SPBP complex is served by two major freeways (I-710 and I-110) and by the Alameda rail corridor. To keep this study manageable while capturing a large share of the impacts of shifting some container traffic from trucks to trains, a study area was selected that extends from the SBPB complex to the edge of downtown Los Angeles (see Figure 1). It includes the two major freeways serving the SPBP complex (I-710 and I-110), the major cross-freeways, the Alameda corridor rail link, and the main rail yards in the area.

The SPBP complex is supported by three types of rail yards—on-dock, near-dock, and off-dock—defined by their proximity to the port terminals. On-dock rail yards are located within the marine terminal and are the focus of this study; they allow cargo to be trans-



(a) (b)

FIGURE 1 (*a*) Freight corridor and (*b*) on-dock rail yards linked to San Pedro Bay Ports.

ported without gate transactions and without truck dispatches. This study analyzes the environmental impacts of shifting freight from long-haul truck trips to on-dock trains. Analyzing near-dock and off-dock rail would be significantly more complex, as it would also involve truck trips on surface streets for which traffic volumes are often unavailable. Within the SPBP, there are nine on-dock rail yards; five of them are located in the Port of Long Beach (Piers J, G, A, and T, and Middle Harbor Terminal), and four are in the Port of Los Angeles [the Terminal Island Container Transfer Facility (TICTF) Shared On-Dock, Pier 300, Pier 400, and the West Basin Intermodal Container Transfer Facility (WBICTF)]; the right panel of Figure 1 shows these rail yards. The Pier B rail yard is considered a near-dock facility (*6*).

METHODOLOGY

To quantify the impacts of a modal shift on the truck emissions of NO_X and particles less than 2.5 μm in diameter ($PM_{2.5}$), two types of models were used: (*a*) a microscopic traffic simulation model and (*b*) a model to estimate the emissions of various pollutants. As a starting point, we analyzed the impacts of modal shift for the year 2005 primarily for consistency with CARB's 2006 emissions reduction plan, but also to use results from previous analyses (*5, 14, 15*).

For trucks, the modeling framework detailed by Lee et al. was adopted; it is summarized in the left half of Figure 2 (*14, 16*). After deciding on a level of modal shift, a revised origin–destination (O-D) matrix was estimated and microscopic simulations performed using TransModeler until a satisfactory match was obtained with traffic counts from the Freeway Performance Measurement System (PeMS) used by the California Department of Transportation (*13*).

Estimates of Emissions

To estimate the resulting air pollutant emissions, it would have been preferable to rely on a microscopic emission model (either the Comprehensive Modal Emissions Model or the Virginia Tech Microscopic Model), but this could not be done because of two of their current limitations. First, available microscopic emission models do not have emission factors for the most recent heavy-duty trucks, and more important, these models are currently unable to model PM emissions from heavy-duty vehicles. To circumvent these limitations, EMFAC2007 emission factors were combined with detailed information about the trajectories of each simulated vehicle to obtain estimates of pollutant emissions (*17*). This application of EMFAC2007 is distinct from the macroscopic emissions estimation approach in which emissions are calculated by applying emission factors to average traffic speed over a network. By contrast, the speed of each vehicle on each link was considered to take advantage of the information generated by microscopic simulation.

For trains, the methodology developed in Sangkapichai et al. was used; it is summarized in the right half of Figure 2 (*15*). The number of trains necessary to haul the additional container traffic was calculated along with the corresponding number of locomotives; line-haul emissions were then estimated using emission factors and distance traveled in the Alameda corridor. Both line-haul and switching locomotives were assumed to belong to Tier 1 [see Sangkapichai et al. (*15*)]. In addition, emissions from rail yard activities were scaled to reflect changes in train operations. Results from train and truck analyses were then aggregated and compared to the baseline.

Obtaining reliable simulations of truck activities for every business day in 2005 would be extremely time consuming and impractical for

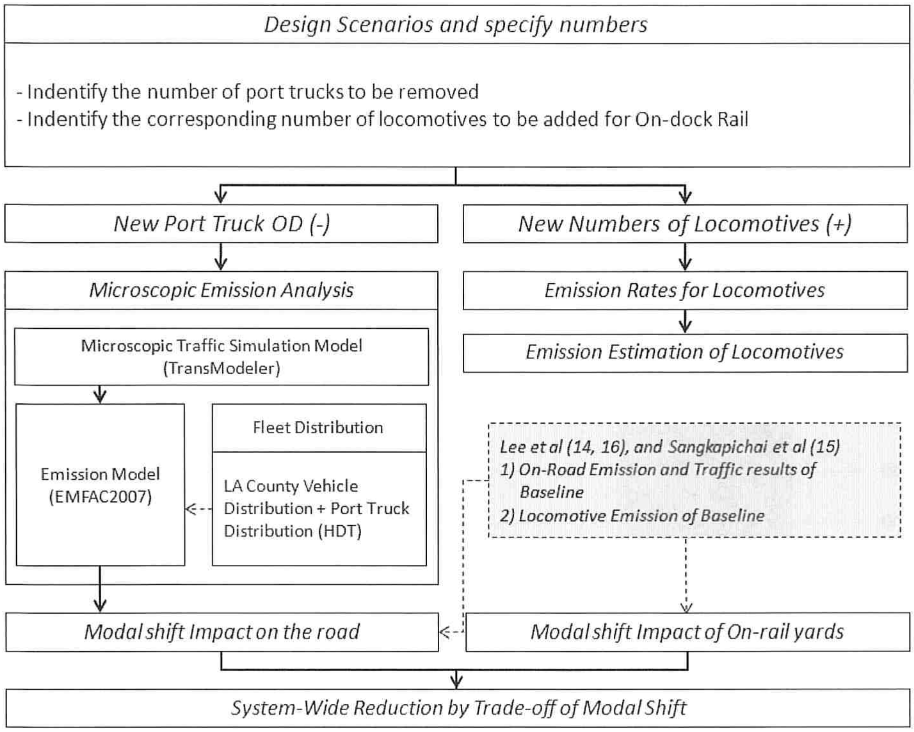

Design Scenarios and specify numbers
- Indentify the number of port trucks to be removed
- Indentify the corresponding number of locomotives to be added for On-dock Rail
New Port Truck OD (-)
New Numbers of Locomotives (+)
Microscopic Emission Analysis
Microscopic Traffic Simulation Model (TransModeler)
Emission Model (EMFAC2007)
Fleet Distribution
LA County Vehicle Distribution + Port Truck Distribution (HDT)
Emission Rates for Locomotives
Emission Estimation of Locomotives
Lee et al (14, 16), and Sangkapichai et al (15)
1) On-Road Emission and Traffic results of Baseline
2) Locomotive Emission of Baseline
Modal shift Impact on the road
Modal shift Impact of On-rail yards
System-Wide Reduction by Trade-off of Modal Shift

FIGURE 2 Framework of modal shift impact analysis.

several reasons; cleaning up detector data from PeMS takes time, as does running a large number of simulations, especially in congested conditions. After comparing speed contours and total traffic volumes for 2005, Wednesday, March 9, 2005, was determined to be representative of weekday traffic conditions at the SPBP complex. The study therefore focused on obtaining calibrated simulation results for that day. Based on the volume of overall traffic and also SPBP truck traffic, traffic conditions in the network were classified as follows: (*a*) morning (from 7:00 a.m. to 9:00 a.m.), (*b*) midday (from 9:00 a.m. until 3:00 p.m.), and (*c*) afternoon (from 3:00 p.m. until 7:00 p.m.). These three time periods have distinct traffic (and truck volume) characteristics, and they correspond to the time periods adopted by SCAG in its O-D estimation procedures (*3*). Night traffic was not considered because in March 2005, SPBP was operating from 8:00 a.m. until 6:00 p.m. The first hour (7:00 to 8:00 a.m.) was considered to catch the early SPBP truck traffic; likewise, the last hour (6:00 to 7:00 p.m.) was used to capture the last flow of trucks leaving the SPBP complex for the day. Then, for each time period, the busiest hour and least-busy hour were simulated to obtain upper and lower bounds for congestion and for emissions.

This approach is summarized in Figure 3. A sum of the emissions for the three busiest hours weighted by the number of hours in each period gives an upper bound for traffic emissions during the 12 h for which port trucks were operating; likewise, the sum of emissions for the three least busy hours weighted by the number of hours in each period (2 h for the morning period, 6 h for midday, and 4 h for the afternoon period) gives a lower bound for traffic emissions during the 12 busiest hours of the day.

Description of Alternative Scenarios

As a first step, emissions on a typical 2005 day were analyzed for the two following scenarios under the assumption of there being no demand changes from 2005 traffic levels:

Scenario 1. Shift containers from trucks to trains to use half of the unused rail capacity and

Scenario 2. Shift containers from trucks to trains to use all of the unused rail capacity.

The proposed scenarios differ in the number of trucks affected by the switch to on-dock rail, which is specified by the volume of unused rail capacity in 2005. In 2005, the maximum capacity of on-dock rail was estimated at 3,832,499 TEU container units (27% of total port throughput). The actual 2005 on-dock throughput was 2,934,850 TEUs; thus, 897,469 TEUs of unused capacity remained (*6*). To quantify the emission impact of a modal shift, it is necessary to consider a potential diversion rate between port heavy-duty trucks and locomotives. The following list describes the methods and assumptions by which TEUs were converted to trucks:

1. The number of port trucks to be shifted is produced by the share of hourly port truck distribution within the upper bound or lower bound.
2. Only on-dock traffic is considered.
3. Unit trains have between 115 and 140 rail cars, with each rail car carrying two stacked 40-ft containers (four TEUs); given an industry-average 90% utilization rate, unit trains can be up to 8,000 ft long and carry between 414 and 504 TEUs.
4. Each train is assumed to have four Tier 1 locomotives.
5. Most trucks carry 40-ft containers, while some carry 20-ft containers; the average truck is assumed to carry 1.8 TEUs.
6. Port trucks operate between 8:00 a.m. and 6:00 p.m. (Monday through Friday), and it takes 1 h to clear port-related truck traffic before and after operational hours.
7. Rail yards operate 24 h/day, Tuesday through Saturday.

On the basis of Assumptions 2, 5, and 6, the number of containers corresponding to unused capacity was converted to 1,870 trucks per

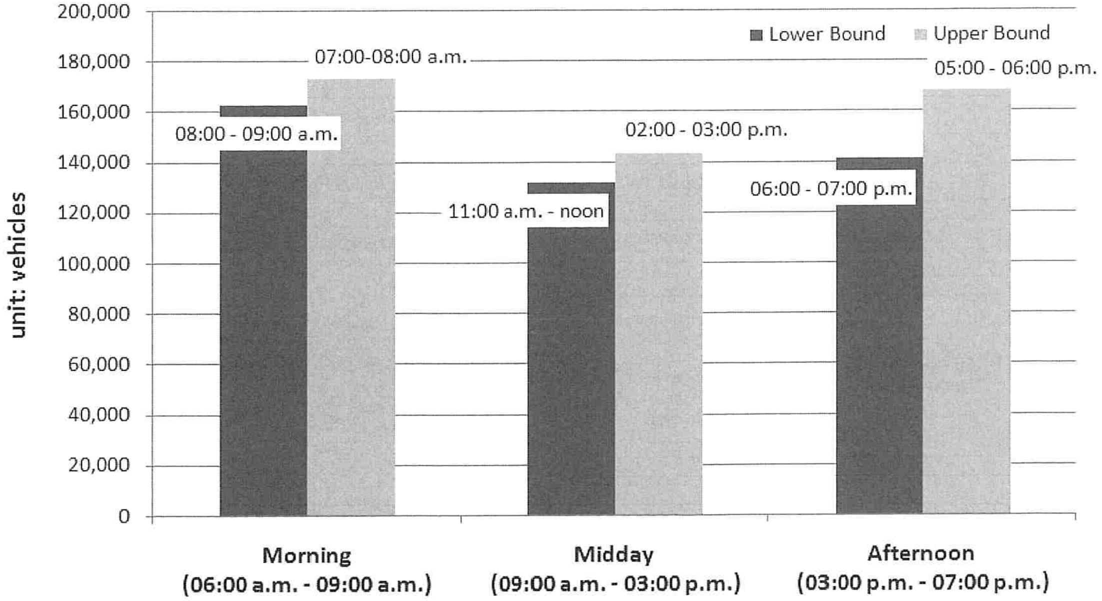


FIGURE 3 Comparison of total traffic volumes for representative hours.

TABLE 1 Number of Port Trucks to Be Shifted: Upper Bound

	Number of Port Trucks to Remove			Number of Trains to Add
	Morning (7:00–8:00 a.m.)	Midday (2:00–3:00 p.m.)	Afternoon (5:00–6:00 p.m.)	Operation Hours (24 h)
Hourly port truck distribution (%)	10.0	11.5	7.0	—
Scenario 1	95	107	66	3
Scenario 2	191	215	131	6

working day. For locomotives, three additional trains for Scenario 1 and six trains for Scenario 2 are needed daily at on-dock rail yards from Assumptions 3, 4, and 7. The corresponding values for each of the two scenarios are shown in Tables 1 and 2.

TRAFFIC SIMULATION RESULTS

Due to the stochastic nature of microscopic traffic simulation, 30 runs for each scenario were generated in TransModeler to obtain estimates of mean emissions and to facilitate statistical testing (based on the central limit theorem). The traffic simulation results shown in Table 3 are based on total working hours for both the upper and the lower bounds.

Table 3 reports three performance measurement statistics for the baseline and the two scenarios considered: VMT, vehicle hours traveled (VHT), and average vehicle speed (Q, in mph) (*18*). Vehicle class counts are also provided.

In a comparison of Scenarios 1 and 2 with the baseline, congestion decreases as Q is slightly higher and both VMT and VHT are lower, so traffic performance is improved. This is because heavy-duty vehicles experience longer headway and inferior performance on grades during congested traffic conditions (*19*). This improvement in traffic congestion can be credited to a reduction in the percentage of port trucks among all vehicles. Compared to the baseline, the number of port trucks decreases by 0.02% to 0.06% and by 0.1% to 0.3% under Scenarios 1 and 2, respectively. Because of the higher share of port trucks in the lower bound case, modal shift affects total traffic slightly more. Although the percentage reduction in port trucks among all vehicles is relatively small, the emission reduction effect for overall $PM_{2.5}$ and NO_X is substantial (emission results are discussed below). Another notable impact is on VHT, which indicates that vehicle interactions such as stop-and-go and acceleration and deceleration are affected by port trucks.

EMISSION RESULTS

Emission Reductions from Port Trucks

Port truck emission reductions related to each of the scenarios are summarized in this section. To evaluate the statistical differences for each pollutant emission between the baseline and each of the scenarios, two-sample z-tests were conducted at the $\alpha = 0.05$ significance level. These tests can be described as follows.

Two-Sample z-Tests (Base Scenario Versus Alternative Scenarios)

$$H_0 : \mu_{\text{emissiontype,base}} = \mu_{\text{emissiontype,scenario}} \text{ versus}$$

$$H_1 : \mu_{\text{emissiontype,base}} \neq \mu_{\text{emissiontype,scenario}}$$

$$Z = \frac{\left(\hat{X}_{\text{emissiontype,base}} - \hat{X}_{\text{emissiontype,scenario}}\right)}{\sqrt{\left(\dfrac{\sigma^2_{\hat{X}_{\text{emissiontype,base}}}}{n_{\text{emissiontype,base}}} + \dfrac{\sigma^2_{\hat{X}_{\text{emissiontype,scenario}}}}{n_{\text{emissiontype,base}}}\right)}}$$

where

$\hat{X}_{\text{emissiontype,base}}$ = average rate of each emission type by scenario,
$\sigma^2_{\hat{X}_{\text{emissiontype,base}}}$ = variance of each emission type by scenario, and
n = number of observations (here, $n = 30$).

TABLE 2 Number of Port Trucks to Be Shifted: Lower Bound

	Number of Port Trucks to Remove			Number of Trains to Add
	Morning (8:00–9:00 a.m.)	Midday (11:00 a.m.–noon)	Afternoon (6:00–7:00 p.m.)	Operation Hours (24 h)
Hourly port truck distribution (%)	10.2	11.7	6.5	—
Scenario 1	93	110	61	3
Scenario 2	187	219	121	6

TABLE 3 Summary of Traffic Simulation Results (total working hours: 12)

	Upper Bound			Lower Bound		
	Baseline	Scenario 1	Scenario 2	Baseline	Scenario 1	Scenario 2
Vehicle miles traveled	10,593,439	10,591,471	10,579,149	9,810,107	9,804,218	9,783,844
(% difference compared with baseline)		(−0.02%)	(−0.1%)		(−0.06%)	(−0.3%)
Vehicle hours traveled	252,202	250,362	249,953	189,359	189,119	187,692
(% difference compared with baseline)		(−0.7%)	(−0.9%)		(−0.1%)	(−0.9%)
Average vehicle speed (Q) (mph)	42.00	42.30	42.32	51.81	51.84	52.13
Number of vehicles (%)						
Passenger cars	1,694,441	1,694,654	1,696,171	1,506,219	1,507,339	1,507,086
	(90.3%)	(90.3%)	(90.4%)	(80.2%)	(80.3%)	(80.3%)
Light-duty trucks	60,378	60,452	60,442	55,794	55,851	55,790
	(3.2%)	(3.2%)	(3.2%)	(3.0%)	(3.0%)	(3.0%)
Medium-duty trucks	27,660	27,576	27,601	25,876	26,083	26,111
	(1.5%)	(1.5%)	(1.5%)	(1.4%)	(1.4%)	(1.4%)
Nonport heavy-duty trucks	35,337	35,306	35,474	33,521	33,686	33,764
	(1.9%)	(1.9%)	(1.9%)	(1.8%)	(1.8%)	(1.8%)
Port heavy-duty trucks	59,226	58,112	56,884	56,178	55,131	53,567
	(3.2%)	(3.1%)	(3.0%)	(3.0%)	(2.9%)	(2.9%)
Total	1,877,041	1,876,100	1,876,572	1,677,587	1,678,089	1,676,318
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)
Modal shift impact on port trucks (%)	—	1.61%	3.29%	—	1.70%	3.49%
(total vehicles)		(0.05%)	(0.1%)		(0.06%)	(0.1%)

Figure 4 gives the percentage change for each pollutant under Scenarios 1 and 2 compared with the baseline, and it reports results of the hypothesis tests. Table 4 shows the average emissions rate by vehicle type for the baseline and for the scenarios considered.

Table 4 shows that NO_X and PM emissions are dominated by heavy-duty vehicles for all scenarios. In contrast, most CO and HC emissions come from passenger cars. Hypothesis tests comparing emissions under the baseline and under the alternative scenarios are statistically significant except for CO and HC emissions for total vehicle emissions in Scenario 1. However, results for Scenario 2, which involves removing more port trucks than Scenario 1, show that the decrease in the emissions of all pollutants is statistically significant and larger than for Scenario 1. In particular, Figure 4*a* shows decreases of 1.4% for NO_X and 1.7% for $PM_{2.5}$ compared with overall emissions by eliminating port trucks that make up approximately 0.05% of total traffic in Scenario 1. Positive effects are found for Scenario 2. Likewise, considering only port trucks, Figure 4*b* shows significant reductions in all pollutants (approximately 4.6% to 5.6% for Scenario 1 and approximately 9.0% to 10.2% for Scenario 2.)

The absolute emissions associated with all scenarios are described in Table 4. Some nonport vehicle emissions are not consistently reduced because reductions in port trucks in the alternative scenarios allow other vehicles to use the network, and therefore the increased VMT causes more emissions. Reductions in port trucks are not intended to increase the traffic of passenger vehicles, but they partly have that effect; these are referred to as secondary impacts. Although secondary impacts exist, the overall results show significant improvements in air quality. Emissions of NO_X and $PM_{2.5}$ generated by port trucks represent 33.5% and 25.7% of the total for the upper bound of the base scenario, but they decrease to 32.3% and 24.6% under Scenario 1 and to 31.2% and 23.8% under Scenario 2.

Emission Changes for Locomotives

For estimating line haul emissions from locomotives, the procedures presented by Sangkapichai et al. were followed to obtain daily emission rates for NO_X and particles less than 10 μm in diameter (PM_{10}) (*15*). For consistency with the freeway emissions results, daily emissions rates were calculated and PM_{10} converted to $PM_{2.5}$ following CARB's size fraction data (*20*).

Tables 5 and 6 summarize emission increases from increased rail operations. The upper and lower bounds of traffic are not considered in the train movement analysis; average train traffic volumes are used. With the emission factors for locomotives and all the information mentioned above, Scenarios 1 and 2 respectively generate 1,897.8 kg/day and 2,009.4 kg/day of NO_X as well as 44.7 kg/day and 47.4 kg/day of $PM_{2.5}$. Details regarding the estimation of locomotive emissions are presented in Tables 5 and 6.

Overall Impacts of Modal Shift

The emissions of on-road vehicles and locomotives are estimated on a daily basis during port and rail yard operating hours. Results are summarized in Table 7. For Scenario 1, NO_X emissions were reduced by approximately 150 kg from port trucks, while the locomotives that carried the same amount of truckload freight produced 111.7 kg of NO_X; thus, the estimated net change in NO_X was approximately 40 kg. For the same scenario, the net reduction in $PM_{2.5}$ emissions is at most 0.8 kg. Reductions for Scenario 2 are larger than those for Scenario 1, but emission reductions are not proportional, because emission rates rely not only on VMT but also on traffic parameters such as speed. From the perspective of overall system-wide reduction, more significant benefits result from reducing NO_X emissions. Even considering secondary effects, the difference between

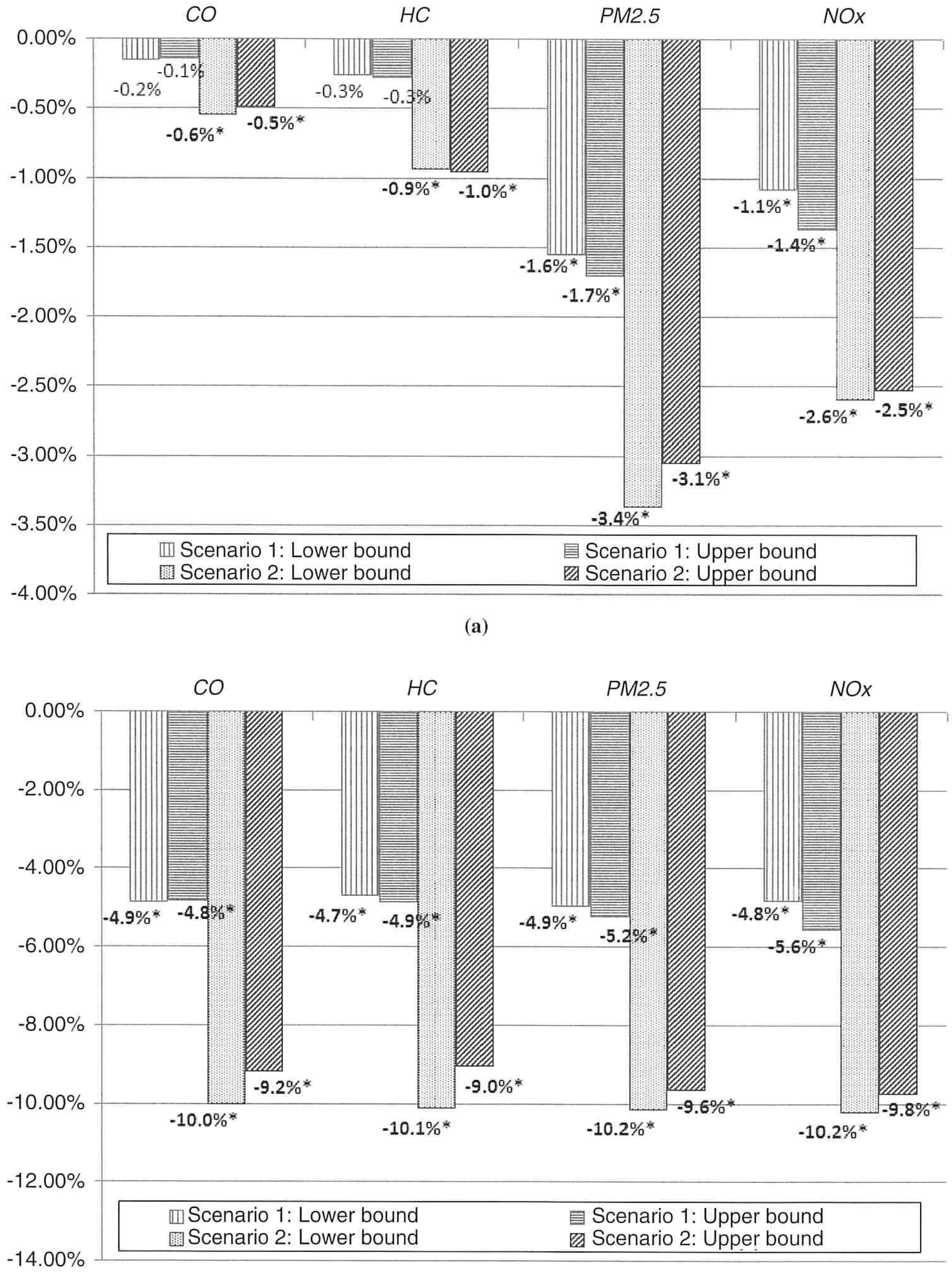


FIGURE 4 (*a*) Daily percentage changes in pollutants compared with baseline (all vehicles) and (*b*) daily percentage changes in pollutants compared with baseline (port trucks only) (* = statistically significant).

TABLE 4 Average Emission Results for All Scenarios (total working hours: 12)

		Upper Bound (kg)				Lower Bound (kg)			
Scenario	Vehicle Type	CO	HC	NO_X	$PM_{2.5}$	CO	HC	NO_X	$PM_{2.5}$
Base scenario	LDV	33,359.7	1,630.5	3,539.7	131.4	30,208	1,441	3,240.9	117.7
		(289.1)	(11.6)	(36.4)	(0.9)	(105.8)	(4.8)	(12)	(0.4)
	LDT	1,752.5	81.8	241.5	7.8	1,673.4	75.2	234.3	7.2
		(37.9)	(1.9)	(5.6)	(0.2)	(16.6)	(0.8)	(2.4)	(0.1)
	MDT	943	41.8	145.9	3.9	917.2	38.9	144.5	3.7
		(27.4)	(1.3)	(4.4)	(0.1)	(13.5)	(0.6)	(2.1)	(0.1)
	HDT	1,632.6	140.3	1,954.1	42.7	1,424.1	109.3	1,907.8	39.7
		(63.4)	(11.5)	(60.4)	(1.7)	(23.9)	(2.8)	(30)	(1)
	Port truck	2,394.4	199.8	2,958.1	64.4	2,279.1	177.3	3,023.4	63.6
		(48)	(9)	(50.3)	(1.5)	(34.8)	(4.1)	(39.4)	(1.2)
	Total	40,082.2	2,094.1	8,839.3	250.3	36,501.8	1,841.7	8,550.9	231.8
		(306.6)	(23.5)	(126.1)	(3.3)	(117.5)	(7.7)	(50.6)	(1.6)
Scenario 1	LDV	33,419	1,633.5	3,546.7	131.7	30,244.1	1,443.1	3,244.6	117.8
		(299.9)	(13.8)	(36.3)	(1.1)	(114.4)	(5.8)	(12.7)	(0.5)
	LDT	1,751.3	81.8	241	7.8	1,676.7	75.4	234.7	7.2
		(35.2)	(2)	(5.1)	(0.2)	(13.5)	(0.6)	(1.9)	(0.1)
	MDT	942	41.8	145.8	3.9	924.5	39.2	145.6	3.7
		(27.7)	(1.3)	(4.5)	(0.1)	(20.2)	(0.9)	(3.2)	(0.1)
	HDT	1,635.4	141	1,951.6	42.7	1,433.7	110.2	1,919.3	40.1
		(56.6)	(9)	(65.6)	(2)	(27)	(2.9)	(53.3)	(1.5)
	Port truck	2,278.6	190.1	2,803.7	60.8	2,168.6	169	2,874	60.5
		(40.3)	(7.4)	(56.5)	(1.7)	(26.3)	(4)	(43.2)	(1.1)
	Total	40,026.4	2,088.2	8,688.9	246.9	36,447.6	1,836.9	8,418.2	229.3
		(370.1)	(25.2)	(146.2)	(4.3)	(122.6)	(8.7)	(73.5)	(1.9)
Scenario 2	LDV	33,397.4	1,630.3	3,545.9	131.5	30,214.5	1,440.1	3,243.1	117.6
		(287.8)	(10.8)	(38.9)	(0.9)	(124.2)	(5)	(14.7)	(0.4)
	LDT	1,748.1	81.4	241	7.7	1,679.1	75.5	234.9	7.2
		(37.2)	(1.7)	(6)	(0.2)	(20.9)	(1)	(2.8)	(0.1)
	MDT	937.7	41.4	145.3	3.9	921.9	39	145.2	3.7
		(27.8)	(1.3)	(4.6)	(0.1)	(15.1)	(0.6)	(2.4)	(0.1)
	HDT	1,629.3	139.3	1,964.2	42.7	1,435.2	110.5	1,923.8	40.1
		(57.6)	(11.4)	(61.7)	(1.8)	(22.2)	(2.6)	(33.6)	(1.1)
	Port truck	2,174.4	181.7	2,672.9	58.2	2,050.6	159.4	2,716.2	57.1
		(48.2)	(10)	(50.6)	(1.4)	(20.5)	(3.6)	(43.4)	(1.4)
	Total	39,886.9	2,074.1	8,569.3	244	36,301.3	1,824.5	8,263.2	225.8
		(306.8)	(25.9)	(132.4)	(3.1)	(128.4)	(6.7)	(64)	(2)

NOTE: ( ) = standard deviation, LDV = light-duty vehicle, LDT = light-duty truck, MDT = medium-duty truck, HDT = heavy-duty truck.

reduced truck emissions and additional locomotive emissions is positive.

These results are persuasive enough to propose a modal shift strategy for mitigating truck emissions. This modal shift can also be expected to have an impact on the dispersion of air pollutants. Indeed, Wu et al. report that pollutants such as NO_X and $PM_{2.5}$ are concentrated downwind immediately after their release, and they tend to accumulate in several areas that include residential and commercial facilities as well as public schools (*21*). Therefore, it is essential to assess not only daily impacts such as those shown in Table 7, but also longer-term environmental impacts.

TABLE 5 Line Haul Characteristics

Segment	Distance (mi)	Speed Limit (mph)	Assumed Notch	Number of Locomotives/ Train for Baseline	Number of Trains/ Day for Baseline
1	8	25	3	4	48
2	10	40	5	4	48
3	2	25	3	4	48

CONCLUSIONS AND FUTURE RESEARCH

The objective of this paper was to quantify the environmental impacts of shifting containers transported by heavy-duty diesel trucks to on-dock trains. The paper analyzed the impacts of modal shift on the freight corridor containing six different freeways and nine on-dock rail yards directly linked to the SPBP. In particular, microscopic simulation was relied upon to capture detailed individual vehicle dynamics such as stop-and-go situations.

Results of two modal shift scenarios with different port truck reductions were evaluated against the 2005 baseline year. Heavy-duty truck-oriented pollutants such as NO_X and $PM_{2.5}$ were significantly reduced by taking port trucks off the road. Systemwide emissions reductions were achieved because of a lesser gain in locomotive emissions. In particular, emission results include traffic-related benefits such as reduced traffic congestion and more stable speeds, with smoother traffic characterized by less acceleration and decel-

TABLE 6 Emission Increases from Rail Operations

		Baseline		Scenario 1		Scenario 2	
Segment	Emission Factor (g/h)	No. of Locomotives per Day	Emission Rate (kg/day)	No. of Locomotives per Day	Emission Rate (kg/day)	No. of Locomotives per Day	Emission Rate (kg/day)
NO_X							
1	7,267	192	446.5	204	474.4	216	502.3
2	25,584	192	1,228.0	204	1,304.8	216	1,381.5
3	7,267	192	111.6	204	118.6	216	125.6
Total	—	—	1,786.1	—	1,897.8	—	2,009.4
$PM_{2.5}$							
1	427	192	24.1	204	25.7	216	27.2
2	348	192	15.4	204	16.3	216	17.3
3	427	192	6.1	204	6.4	216	6.8
Total	—	—	45.6	—	48.4	—	51.3

NOTE: NO_X (or $PM_{2.5}$) = travel time × no. of locomotives/train × no. of trains/hour × emission factor.

TABLE 7 Daily Potential Emission Impacts of Modal Shifts to Rail (kilograms per day)

	Scenario 1				Scenario 2			
	NO_X		$PM_{2.5}$		NO_X		$PM_{2.5}$	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Modal shift								
Reduced port truck emissions	154.4	149.4	3.6	3.1	285.2	307.2	6.2	6.5
Additional locomotive emissions	111.7		2.8		223.3		5.7	
Net change	42.7	37.7	0.8	0.3	61.9	83.9	0.5	0.8
Reduced total emissions	150.4	132.7	3.4	2.5	270.0	287.7	6.3	6.0
Systemwide reduction (%)	0.5%	0.4%	0.3%	0.1%	0.7%	1.0%	0.2%	0.4%

NOTE: Net change = Reduced port truck emissions − additional locomotive emissions; systemwide reduction = (reduced total emissions − additional locomotive emissions)/baseline total emissions for NO_X (or $PM_{2.5}$) × 100%.

eration. The findings show that a modal shift has the potential to reduce emissions in the vicinity of the SBPB complex. The benefits of modal shift will be strengthened with the Rail Enhancement Program (REP) and the 2008 EPA emissions regulations for diesel locomotives. REP increases rail yard capacity so that more containers can be handled, and the 2008 EPA emission regulations that gradually clean up locomotives will start to take effect (*22*).

In a parallel effort, the impacts of the Clean Truck Program are being studied by the authors of this paper. In the future, in order to better understand the impacts of port-related heavy-duty vehicles on neighboring communities, these authors will also study local street emissions and attempt to assess the air quality impacts of freight transportation at near-dock and off-dock rail yard locations.

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The Intermodal Freight Transport Committee peer-reviewed this paper.

Multimodal Approach to Low-Cost Improvements Addressing Freight Mobility Constraints

Edward Fekpe

Freight mobility is constrained not only by physical infrastructure inadequacies but also by operational, regulatory, policy, technological, and financial limitations. The capacity of the existing freight transportation system can be increased through innovative operational strategies, performance-improving regulatory and policy changes, and low-cost capital improvements. This paper defines freight mobility constraints in a multimodal context, identifies the primary causes of the constraints, develops criteria for low-cost improvements that can be quickly implemented, and presents examples of practical, low-cost improvements to address mobility constraints encountered in moving freight by highway, by rail, and through deepwater ports and inland waterways. The paper also presents the framework for a methodology that can be used by public-sector agencies to evaluate mobility constraints and select low-cost improvements derived from implemented projects.

The rapid growth in freight demand over the past 15 years has produced growing concerns regarding the capacity of the freight transportation system to support and sustain safe and efficient freight mobility. Inadequate capacity and increasing congestion occur not only on the nation's highways but also in metropolitan areas, at ports, and at railroads, airports, and intermodal facilities.

Freight mobility is constrained not only by physical infrastructure inadequacies but also by operational, regulatory, policy, technological, and financial limitations. The ability of federal, state, and local transportation agencies to invest in system expansion and new system technology has been significantly constrained by inadequate revenue. The capacity of the existing freight transportation system can be increased through innovative operational strategies, performance-improving regulatory and policy changes, and low-cost capital improvements. There is no single or simple solution to mobility challenges. A practical approach should consider the entire freight transportation system rather than mode-specific solutions.

This paper defines freight mobility constraints in a multimodal context and develops criteria for low-cost physical, operational, and regulatory improvements that can be quickly implemented. The paper also presents a catalogue of low-cost improvements to address freight mobility constraints on highway, rail, and water modes. The paper also presents the framework for a methodology that can be used by public-sector agencies to evaluate mobility constraints and select low-cost improvements based on projects implemented elsewhere.

Information presented in this paper is based on an ongoing National Cooperative Freight Research Program (NCFRP) project intended to develop a greater understanding of the dimensions of the freight system and to develop methodologies that private- and public-sector decision makers can use to identify, categorize, and evaluate quickly implementable, low-cost capital, operational, regulatory, and public policy actions to reduce system constraints.

PREVIOUS STUDIES

Highways

Previous studies on freight mobility issues have tended to focus on physical constraints on the highway system. Although these studies attempted to identify some of the causes and locations of these constraints, they did not define what constitutes a "freight mobility constraint." For example, FHWA categorizes freight mobility problems into four constraint types: interchange constraints, highway capacity constraints, geometry constraints (e.g., steep grades), and intersection-related constraints (*1*). An ongoing NCHRP project has identified a number of physical or geometric features that contribute to the occurrence of freeway bottlenecks (*2*).

Although certain improvements that have been implemented to improve freight mobility may be considered low-cost, there is no general definition of the characteristics of low-cost activities, and various agencies define them differently. For example, the Minnesota Department of Transportation used criteria comprising four elements to identify "short-term, low-cost congestion-reduction strategies" for specific bottleneck locations (*3*).

Latham and Trombly defined low-cost traffic engineering improvements to be "project[s] or strateg[ies] that generally [require] an investment in the range of $10,000 to $50,000" (*4*). In addition, the authors stated that "low-cost traffic engineering improvement techniques are typically spot applications or are limited to shorter sections of roadway that do not cover an entire length of an arterial corridor." Latham and Trombly, FHWA, and Walters et al. have presented examples of successful low-cost physical improvements to address physical constraints on highways (*4–6*).

In addition, FHWA has identified 12 low-cost operational remedies directed at addressing congestion and suggested that improving the management and operation of transportation systems is a cost-effective way to influence the bottlenecks that affect freight (*5, 7*). O'Laughlin et al. suggested regulatory actions that include new building standard policies for added improvement and efficiency with freight mobility

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(e.g., a comprehensive loading zone plan), including creating a physical inventory of loading zones or adding loading zones in "hot spots" (*8*).

Rail

Railroads are also beginning to experience severe capacity constraints in areas where commuter and intercity passenger rail services share tracks with freight railroads (*9*). Immel and Burgel noted that rail capacity is also affected by (*a*) speed and length of trains; (*b*) differing priorities; and (*c*) the number and types of facilities in the same area served by the rail lines (*10*). Adding capacity may require changes in operating practices and investment in tracks, signals, and other facilities that directly affect capacity. Some of the rail freight mobility constraints identified in the literature include inadequate sidings, outdated communication and signaling systems, switching conflicts, a lack of funding for track upgrades, and limited capacity of yards and port terminals. However, there is no clear definition of "freight mobility constraint" from the rail perspective.

Improvements to rail capacity range from costing little to being very expensive. Some of the improvements that fall within the low end of the cost spectrum include track improvements (e.g., improved passing sidings), upgraded communication systems, joint use of facilities, and pairing mainlines to provide directional running. The characteristics of low-cost actions or strategies directed at addressing rail freight mobility constraints are not defined in the literature.

Deepwater Ports and Inland Waterways

Freight mobility constraints are not defined for movements through the marine transportation system, which includes interrelated components of the national transportation system such as shipping, ports, inland waterways, and their connections to rail and highway transportation modes and systems (*9*). There is also no definition of a low-cost action or strategy. Certain actions directed at improving freight mobility could be characterized as such given the potential for their having lower costs as compared with massive seaport terminal projects (*9*). Examples include improving marine terminal capacity and access to rail, roads, and pipelines; improving signage; and increasing the number of hours and shifts that terminal gates are open.

DEFINITION OF MOBILITY CONSTRAINT

In defining "freight mobility constraint" properly in a multimodal context, information was gathered through a literature review, interviews, and a survey of representatives of various public- and private-sector stakeholders involved in freight transportation. These include state departments of transportation (DOTs), metropolitan planning organizations (MPOs), trucking companies, railroad companies, freight shippers and forwarders, deepwater port terminal operators, and federal agencies. A freight mobility constraint has been defined in the following ways:

- Any infrastructure, institutional, financing, operational, or environmental deficiency that impedes or has a significant likelihood of impeding the safe and efficient movement of goods in a sustainable manner;
- Operational, infrastructure, or institutional issues that prevent the free or unencumbered flow of freight;
- Any event, situation (e.g., construction, a customs or border delay, or a weather-related road closure), or physical feature (e.g., a design deficiency) that affects the movement of freight;
- Impediments or obstacles, including infrastructure, regulations, or congestion, that prevent freight from moving freely, quickly, and efficiently anywhere in the transportation system between the origin and destination of the shipment;
- Any system limitation, policy decision, operational concern, or communication issue that undermines the potential fluidity of any segment of the logistics stream;
- Lack of connectivity between freight modes, congestion-laden networks, or lack of technology or equipment, all of which would hinder the efficient flow of freight traffic; and
- Any internal or external factors that define the limits on the amount of freight that can be moved between two points efficiently, safely, and in an environmentally acceptable way. These factors include the characteristics of the physical infrastructure, operational procedures, and regulatory regimes. Any factor or factors connected with highway operations that significantly add to the cost of moving freight, such as delays, truck operating costs driven by congestion and terrain, or undersized intermodal facilities.

On the basis of the taxonomy of these definitions and the themes they share, a freight mobility constraint is generally defined as "a physical or infrastructure deficiency, regulatory requirement (federal, state, or local), or operational action that impedes or restricts the free flow of freight either at the network level or at a specific location." Mobility constraints increase costs, contribute to system inefficiencies, and delay on-time freight delivery. These constraints can be grouped into three main types.

- Physical constraints. Any geometric or infrastructure conditions that constrain freight operators from operating at designed, safe speeds and within legally required parameters. Examples include inadequate capacity of the transportation system (e.g., mainlines, interchanges, storage, port terminals) and geometric restrictions or limitations affecting safe and efficient mobility.
- Operational constraints. Events or occurrences that constrain system throughput and limit optimal and legal operating conditions. Examples include events or occurrences that constrain legal operating speeds, poor signal phasing, lack of skilled labor, and inadequate traveler information.
- Regulatory constraints. Federal, state, or local regulatory requirements that, while intended to provide an environment for safe and secure operation, have unintended consequences that restrict the flow of freight through the system. Examples include safety and security requirements, truck restrictions, zoning policies, air quality restrictions, labor union policies, and contractual limitations.

PERFORMANCE INDICATORS

The performance indicators used in monitoring and identifying freight mobility constraints vary by mode and agency and are different for the public and private sectors. Public-sector agencies implement improvements to address the constraints with the goal of facilitating safe, secure, and efficient movement of freight. The private sector, however, uses different measures to monitor and identify constraints to its operations and reacts by taking measures

TABLE 1 Primary Causes and Performance Indicators of Mobility Constraints by Mode

Primary Cause	Metrics and Indicators
Highway	
Regulatory constraints Land use controls and regulations Parking restrictions Speed limits Safety regulations Hours of service regulations Highway geometry (e.g., outdated interchange and intersection designs insufficient to meet traffic demand and requirements of longer trucks; roundabouts near freight facilities) Inadequate system management including outdated or inadequate traffic signal systems Inadequate capacity to meet increasing demands Poor road signage, including warning signs	State DOTs and MPOs Average truck speed Delay to traffic Level of service Average daily traffic/truck traffic including percentage of trucks Truck trips per day Motor carriers On-time customer pickup or delivery Driver delay Driver utilization per mile Truck idle time Average truck speed
Rail	
Regulatory constraints (federal and state) Inadequate physical capacity Constrained capital budget Lack of skilled labor Poorly structured labor work rules	Idle time Average train speed Level of service Terminal dwell time On-time customer pickup or delivery
Deepwater Port and Inland Waterways	
Regulatory constraints (e.g., land use controls and regulations) Inadequate capacity of intermodal connectors (truck and rail) Inadequate traffic system management on intermodal connectors Terminal gate operating hours Port terminal processing requirements Security and air quality regulations	Idle time Gate transactions per day Truck trips per day Average speed On-time pickup or delivery Level of service Dwell time in hours or days

that minimize the effects of constraints on the safe, secure, and efficient movement of freight. Table 1 summarizes the primary causes of freight mobility constraints for each mode and shows the metrics that are typically used to monitor and identify the constraints. The performance indicators presented in Table 1 are arranged in order of decreasing popularity of use. Direct and surrogate measures of delay to freight are common performance indicators for all modes.

MAJOR CONSTRAINT TYPES

The predominant type of freight mobility constraint (physical, operational, or regulatory) depends on the primary mode of freight movement. Results from a survey and interviews with stakeholders indicate that regulatory restrictions (in particular federal, state, and local land use and environmental restrictions), technological limitations and inadequacies, and operational limitations are the most common types of mobility constraints affecting all modes of transport. From the private-sector perspective, however, as represented by the motor carrier industry, operational limitations are the most common type of constraints encountered in freight movement.

Although physical and infrastructure deficiencies were identified, these are not considered the most critical constraints affecting freight mobility by both public- and private-sector representatives. This can be explained to some extent by the fact that physical infrastructure features are fixed assets that often require major expenditures to expand their capacity. The capital-intensive projects are constrained by lack of revenue and by strict regulatory controls. Therefore, for a given transportation infrastructure system, it is expected that optimal operations will be affected by operational and regulatory issues. Table 2 presents examples of the common types of freight mobility constraints for the three modes.

Motor carriers identified the following as the three most frequently reported consequences of congestion, delay, and mobility constraints:

1. Increased operating costs,
2. Longer transit time, and
3. Decreased levels of service.

CRITERIA FOR LOW-COST IMPROVEMENTS

Many innovative, low-cost efforts are being implemented by state DOTs, MPOs, shippers, freight carriers, ports, terminal operators, and other groups of stakeholders to address acute local freight mobility problems. Although many promising strategies have been developed and implemented, there are no unique criteria to define what constitutes a low-cost improvement designed to enhance freight mobility. A definition of "low-cost improvement" was developed that satisfies the following criteria:

1. Recognizes the differences in modal capacity requirements and other freight mobility constraints, as well as the cost of improvements to address these constraints. A low-cost action for the rail mode may not necessarily be a low-cost action for the highway mode.
2. Is sensitive to the scale of the mobility constraint.
3. Links to how a particular mode measures successful performance for moving freight through the points where the constraints occur.
4. Considers the type of freight mobility constraint, recognizing that the type of improvement is directly linked to the type of constraint.
5. Considers the implementation period of an improvement. An improvement may be low-cost but not necessarily quickly implementable. The time frame or threshold to define "quickly implementable" should be determined by the nature of the improvement and the mode under consideration.

On the basis of results of the interviews and survey, a "low-cost and quickly implementable" improvement to address freight mobility constraints may be defined as follows: an action that modifies existing geometry and operational features of the freight transportation infrastructure system and that can be implemented within a short period without extended disruption to traffic flow. Such an improvement may be physical, operational, or regulatory, as long as it enables greater throughput from existing facilities. These actions may be

TABLE 2 Common Mobility Constraints by Mode

Mode	Physical Constraints	Operational Constraints	Regulatory Constraints
Highway	Inadequate mainline capacity—inadequate number of lanes Narrow roadway or lanes Inadequate turning intersection radii or channelized turns Inadequate weaving sections Long steep grades with no passing lanes Short interchange ramps No turning lanes at intersections Insufficient parking for trucks Lack of alternate routes for large trucks	Inadequate traveler information; lack of timely traveler information on incidents, weather, temporary road closures, construction zones Poor road signage Poor signal phasing Lack of warning signs on crossroad approaches Lack of 24 × 7 access to intermodal facilities On-street parking, bus, or other roadside activities too close to intersections Inadequate loading zones Lack of drivers	Parking restrictions Truck lane restrictions Speed limit restrictions Route restrictions for long combination vehicle and other trucks Land use controls and regulations Department of Homeland Security and other security requirements Hours-of-service regulations Lack of interoperability in use of toll passes Differences in truck size and weight regulations Lack of reciprocity in truck licensing and inspection
Rail	Mainline throughput capacity Inadequate siding length No passing siding Vertical double stack restrictions	Signaling restrictions or less than optimal signaling—outdated or inefficient signaling and telecommunications Terminals switching inefficiency Inadequate investments in locomotives and freight cars Speed restrictions in urban areas Lack of skilled labor	Federal and state regulations Labor issues—supply, training, and utilization Lack of funding
Deepwater port and inland waterways	Inefficient terminal layout or terminal gate configurations Inadequate capacity of intermodal connectors Small, aging, unreliable locks (lock capacity) Lack of channel depth Flooding and insufficient clearance (inland waterways)	Lack of labor or crew supply Lack of truck appointment pickup and drop-off systems Restricted terminal gate operating hours Inefficient terminal layout Lack of electronic communication in rural areas (inland waterways)	Labor unions and contractual limitations Restrictive security requirements Restrictive air quality requirements

spot (or location-specific) improvements or may be limited to short sections of the physical infrastructure. Likewise, they may be specific to a given supply chain process point, regulation, or mode; they may also be multimodal. Furthermore, low-cost improvements do not involve massive reconstruction of infrastructure, which usually takes many years to complete.

Details on how this definition relates to different modes of transport are provided:

- Highways. Low-cost and quickly implementable improvements do not require special programming, time-consuming environmental clearances, or right-of-way acquisition. They are also within budget limitations, enabling implementation at a district level. A low-cost improvement project is generally considered to cost $1 million or less; a project is considered quickly implementable if it can be completed in 1 year or less.
- Rail. The definition of a low-cost and quickly implementable improvement project varies depending on the category of railroad. For a short-line railroad, a low-cost improvement project is one that costs less than $500,000; a quickly implementable project is one that could be completed in less than 6 months. For a regional railroad of modest size, a low-cost and quickly implementable project would cost less than $2 million and be completed in 2 years. For a major Class I railroad, however, the cost range might be more like $1 million to $10 million. Right-of-way acquisition almost always delays a project and eliminates it from the low-cost category.
- Deepwater coastal ports and inland waterways. Low-cost physical improvements to reduce existing and potential port congestion and enhance land-side freight movement may need to be coordinated with highway and rail improvements both within and outside the terminal. These improvements facilitate intermodal activities (e.g., improvement of rail tracks and switches) and restriping and signal timing changes at intersections leading to port terminals. Operational and regulatory improvements include the use of optical character recognition technology to identify drayage trucks, the use of web-based platforms for exchanging container information between ships and terminal operators (to enhance rapid offloading and loading of containers), adoption of port pricing strategies that encourage pickup and delivery of cargo at less congested times (to reduce freight and passenger congestion on the transportation system), and adoption of strategies to reduce truck waiting and idling times. In addition, those ports and waterways that focus on bulk cargo (such as moving coal to electrical power plants) have implemented barge loading mechanisms and navigation communications as operational improvements designed to meet regulatory safety and environmental requirements. A low-cost and quickly implementable improvement for deepwater ports and inland waterways is defined as one costing up to $1 million and requiring up to 2 years for implementation.

Table 3 summarizes the attributes of quickly implementable low-cost improvements. It is recognized that the cost thresholds in the criteria are average values and can vary in time and space. The cost and duration numbers are based on data from different stakeholders in various parts of the country and should serve only as guides.

TABLE 3 Key Features of Low-Cost and Quickly Implementable Improvements

Characteristic of Low-Cost Actions	Time to Implement
Highway	
Less than $1 million	Less than 1 year
Spot or location-specific improvements	
No minimal environmental clearances necessary	
No right-of-way acquisition	
No special programming required	
Implementation at district lowest operation unit level (limited direct HQ oversight)	
Rail	
Class I railroad: $1 million to $10 million	Less than 2 years
Regional railroad: less than $2 million	Less than 1 year
Short line railroad: less than $500,000	Less than 6 months
Deepwater Ports and Inland Waterways	
Less than $1 million	Less than 2 years
Physical improvements may involve highway and rail projects within and outside the port terminals at links serving ports—location-specific actions	
Mainly operational actions, including technology deployments	
Uniqueness of each port acknowledged	

IMPROVEMENTS

Highways

Table 4 presents examples of public-sector low-cost improvements for different constraints derived from information on implemented projects that satisfy the low-cost improvement and quickly implementable criteria. The table shows commonly used actions and is not exhaustive. There may be variations in the details of actual deployment of certain improvements.

On the basis of information gathered from the survey, Table 5 ranks the top five low-cost physical improvements for highways that are considered to be effective from the perspectives of public-sector (represented by state DOTs and MPOs) and private-sector (represented by motor carriers) stakeholders. Traffic signal synchronization and auxiliary lanes are ranked as being the most effective physical low-cost improvements. This is consistent with earlier findings showing the use of auxiliary lanes to be the most common low-cost bottleneck improvement (*5*).

Motor carriers also listed actions commonly undertaken to avoid or eliminate the effects of constraints on their freight operations. These actions are intended to minimize or overcome the effects of frequently encountered mobility constraints while achieving acceptable productivity levels:

- Use alternate routes,
- Reschedule trip or delivery,
- Deploy in-cab communications, and
- Add equipment, drivers, or resources.

In addition, in response to carriers' needs for more flexibility from drivers, recent labor contracts now allow carriers to use "hybrid" drivers that can be used for both line-haul and local pickup and delivery. Other process improvements to mitigate the effects of mobility constraints include

- More off-peak operations,
- Earlier truck departure times and later arrival times,
- Carrier-imposed restrictions on the movement of high-value shipments,
- Facilitation of data exchange with shippers on the availability of loads and preclearance for pickups or deliveries,
- Greater propensity to operate less-than-full trucks,
- Additional charges for congested areas or facilities,
- Customers allowing more driving time for travel through congested areas or to locations with significant congestion, and
- Customers changing pickup and delivery hours (e.g., providing 24-h access to trailer staging areas and drop yards or encouraging early-morning and late-evening delivery times to help carriers avoid peak travel times).

Rail

Table 6 presents the mobility constraints that are most often encountered and examples of improvements that have frequently been implemented. Operational constraints are more prominent than physical and regulatory constraints. The top five low-cost improvements believed to have a high potential of addressing rail freight mobility constraints are provided in the following list:

1. Deployment of advanced technologies,
2. Train control and advanced dispatching,
3. Advanced electronic inspection techniques,
4. On-board sensors, and
5. Trunked digital communication systems.

Deepwater Ports and Inland Waterways

Table 7 presents examples of common improvements that have been implemented to address mobility constraints often encountered during freight movement through deepwater ports and inland waterways. As with rail, with the water modes, operational constraints are more prominent than physical and regulatory constraints. The top five low-cost improvements believed to have a high potential of improving freight mobility constraints are shown in the following list:

1. Terminal reconfiguration to add more capacity;
2. Wireless communications on terminals to facilitate proper storage, ship operations, and gate operations;
3. Regular planning meetings to coordinate ship, rail, labor, and drayage requirements;
4. On-terminal traffic management; and
5. "Fast lane" at gates using paperless checking.

The constraints and corresponding improvements presented in Tables 4, 6, and 7, together with detailed information on previously implemented projects, are integral components of a methodology for evaluating freight mobility constraints and selecting suitable future improvements. The following section outlines such a methodology.

TABLE 4 Highways: Common Public-Sector Improvements

Constraint	Improvements	
Inadequate turning radii	Add turning lane Widen lane	Extend existing lane Modify median bull noses
Weaving	Add auxiliary lane Extend turning lane Add turning lane	Extend existing lane Redirect traffic Restripe
Inadequate ramp capacity	Add auxiliary lane Add turning lane Add traffic signal Extend acceleration and deceleration lanes Extend ramp length Implement ramp metering	Realign interchange Widen lane Reduce speed Add warning signs Improve road signage Restripe
Inadequate parking	Provide parking areas even with no facilities[a] Pave shoulders	Widen shoulders on mainline and ramps
Inadequate mainline capacity	Add warning signs Add a lane Reduce speed Add channelization	Improve road signage Restripe Upgrade signal Revise merging–diverting area
Inadequate intersection capacity	Add dedicated turning lane Extend turning lane Add auxiliary lane Widen turning lane	Implement signal phasing Improve intersection layout Use proper roundabout design near freight facilities
Operational		
Lack of or poor signal timing	Install signal Upgrade traffic signal	Synchronize signal phasing
Poor signage or warning signs	Improve road signage	Add better and advanced navigational signing
Steep grade with ramp meter	Remove ramp meter Relocate ramp meter	Alter ramp metering operation
Regulatory		
Parking restrictions	Revise parking restrictions Provide additional parking	Allow parking on paved shoulders and ramps[b]
Truck lane restrictions	Modify restrictions	

[a] Likely to meet opposition by truck stop interest competitors.
[b] Risk of crashes and security problems.

FRAMEWORK OF METHODOLOGY

The methodology is embodied in a simple computer-based application in which decision makers make selections to define the constraint and choose possible actions to address it based on improvements previously implemented elsewhere. The user then views example cases or scenarios in which the actions had been implemented or proposed. The framework of the methodology is depicted in Figure 1.

The methodology includes a database of information on historical low-cost improvements that satisfy the definitions presented earlier. The methodology was developed acknowledging that it would be integrated into the standard project development process that each state DOT and MPO is required to have in order to use state or federal funds to implement such projects. The methodology acknowledges that

- Most candidate projects are developed from an approved state or MPO planning process;
- The planning process includes some kind of freight stakeholder input process by which candidate projects are suggested; and
- Some kind of preliminary on-the-ground analysis has been conducted to ensure that the project can be implemented using the resources available and without significant environmental complexities.

The conceptual framework has three main components.

TABLE 5 Ranking of Effective Physical Improvements: Highway

Public Sector (state DOTs and MPOs)	Private Sector (motor carriers)
Traffic signal synchronization	Traffic signal synchronization
Auxiliary lanes	Auxiliary lanes
Truck climbing lanes	Acceleration and deceleration lanes
Improved intersection turn radius	Truck climbing lanes
Truck restrictions	Restriping to add more lanes

Characterization of Constraint

Several steps are involved in characterizing the constraint.

- Select constraint location. The user first selects the freight transportation mode of interest (e.g., highway, rail, or deepwater ports and inland waterways). For the selected mode, the user identifies the

TABLE 6 Railroads: Common Improvements

Constraint	Improvements	
Physical		
Inadequate mainline capacity	New track (siding) Turnout Realign track Upgrade siding track Extend siding track	New mainline track Connection tracks Centralized traffic control system Branch line upgrades
Inadequate siding capacity	Extend siding track	
Inadequate capacity of yards and port terminals	Expand carload terminals Internal gateway facilities	Expansion of intermodal terminals
Operational		
Switching conflicts or inefficient switching	Remote switching Upgrade and reconfigure interlocking	Low-emission switch engines
Outdated communication and signaling	Centralized traffic control system Onboard and wayside defect detection and other advanced sensors	Signal improvements—advanced technologies Trunked digital communications systems
Delay (train trip time)	Advanced electronic inspection techniques Tie replacement Improve crossing warning systems and make current passive crossings active	Turnout Realign tracks Provide crossover Curve superelevation Track surfacing
Lack of skilled labor	Hire temporary workers	

TABLE 7 Deepwater Ports and Inland Waterways: Common Improvements

Constraint	Improvements	
Physical		
Terminal yard–gates—roadway connector	Widen local roads Restripe to add lanes	Auxiliary gate lanes
Terminal yard–gates	Locate secured inspection areas outside major traffic areas	Terminal reconfiguration to add capacity
Rail intermodal connector capacity	Expand rail connections	
Operational		
Lack of crews	Support labor union and training programs	Hire temporary labor
Terminal yard–gates	Expanded gate hours Congestion pricing Trucking appointment system Automated yard marshalling and inventory control Joint inspection facilities Establish flexible labor shifts	Partnership to accommodate uneven demand cycles Utilize wireless communications to facilitate proper storage, ship operations, gate operations High speed gates–fast lane using paperless checking
Terminal yard–gates—roadway connector	Synchronizing traffic lights	Traffic management
Rail intermodal connector	Integrated maritime and rail movements	Fast rail shuttles
Outside the fence—rail intermodal connector	Off-dock container yards	Partnership to reduce passenger or freight rail use conflicts
Regulatory		
Supply chain connectors	Smooth out mismatched labor structures	
Labor laws and restrictive contractual limitations	Negotiate training terms and conditions to increase skills and trained labor supply	
Transportation Worker Identification Credential requirements and lack of card-reading equipment	Use existing software packages for card readers	Upgrade card readers

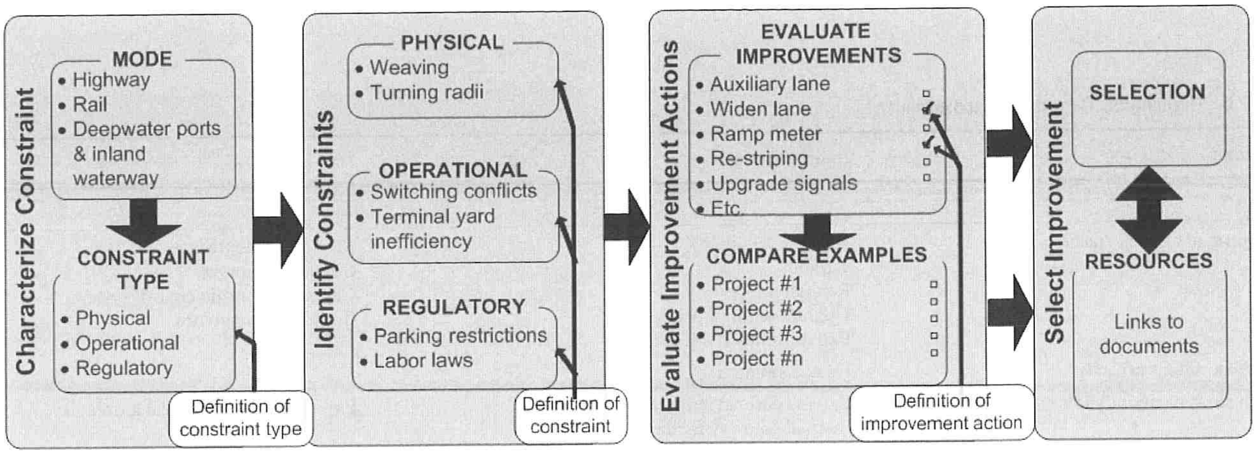

FIGURE 1 Framework of methodology.

subcategory of the mode and the elements of that subcategory. The user will further identify the location within the subcategory where the constraint occurs.

– Highways. Subcategories include the major functional classes (rural and urban), and constraint locations include mainline, interchange ramp, and intersections.

– Rail. Subcategories include Class I, regional, or short-line rail, and the constraint location includes mainline, siding, terminal or yard, or communication improvements.

– Deepwater ports and inland waterways. Subcategories include deepwater ports and inland waterways, and the constraint location would be on the terminal, outside the gate, or waterside (this designates physical zones of operation that require various partners with financial responsibility for implementing actions that address constraints).

- Determine type of constraint. The next step is to classify the constraint into one of three types: physical, operational, or regulatory. Definitions of the different types of constraints are displayed to guide the user.
- Select constraints. For the selected type and location of constraint, a list of constraints that could occur is displayed, from which the user can select the constraint that best fits the situation under consideration. Standard descriptions for the selected constraint are displayed as pop-up boxes to confirm that the selection fits the situation under consideration. This step is illustrated in Figure 1, with examples of physical constraints for the highway mode. Similar lists for the other constraint types and for each mode have been developed.

Selection of Improvement

Once the constraint has been characterized, the user can then select from a list of possible actions that can be used to address that constraint. The improvements displayed are determined by the type of constraint. Examples of improvements are shown in Tables 4, 6, and 7.

After selecting the improvement, the user can view examples of projects implemented. The user can also select multiple improvements and compare the selected actions on the basis of their characteristics or view examples of each action. For each selected constraint, improvements that have been implemented elsewhere are listed.

For the rail mode, because ownership of the railroads is private, public-sector improvements are limited except for regulatory actions. Freight mobility constraints associated with deepwater ports and inland waterway modes are influenced to some extent but not exclusively by the highway and rail intermodal links to the ports. Consequently, some of the physical constraints are influenced by these intermodal connectors. Others, however, are totally within the jurisdiction of private- or public-sector terminal operators and occur within the boundaries under their control.

Evaluation of Improvements

For the selected actions, a list of projects in the database where the action either has been implemented or is under consideration is displayed. The user can also view details of the projects, such as the actual location where the project was implemented (e.g., state), a description of the project, the cost, the duration (where such information is available), performance indicators used, before-and-after values, and lessons learned. Where multiple strategies are selected, the characteristics of these multiple actions can be displayed together so that the user can compare different improvements. In addition, links to sources of more detailed project information are provided to assist users seeking further in-depth information on projects of interest.

IMPLEMENTATION OF METHODOLOGY

The methodology is data driven and therefore, to serve a useful purpose, the database needs to remain dynamic and be continuously updated. It is therefore critical to include a mechanism to keep updating and adding new actions to the database as additional information becomes available. However, no standard process currently exists to define, describe, or measure low-cost freight mobility constraint improvement projects. This process is viewed as a multistate and multiagency effort to collect data on implemented projects to populate and update the database on a continuous basis.

The goal is to encapsulate the methodology in a web-based software application tool once sufficient data are included in the database. A collaborative data collection mechanism is required to facilitate continuous update of the database. Such a mechanism will include a feedback screen to capture strategies selected by policy makers and decision makers to resolve mobility issues. This information will contribute to the database and add intelligence to the application.

CONCLUSIONS

This paper presents a concise definition of freight mobility constraints and identifies three major types of constraints (physical, operational, and regulatory) for freight movement on highways, by rail, and through deepwater ports and inland waterway systems. The paper also develops criteria for characterizing low-cost physical, operational, and regulatory improvements. These definitions and criteria are intended to help public- and private-sector stakeholders adequately assess freight mobility constraints and select suitable, proven improvements. Finally, the paper describes the framework for a methodology that provides a structured approach to identifying and evaluating low-cost capital improvements, innovative operational changes, and regulatory actions to address freight mobility constraints for the primary modes described above.

The concept of operations of the methodology has been tested with sample data and was found to hold promise in developing a dynamically evolving catalogue of strategies that are likely to be of national value for addressing freight constraints. Ultimately, the methodology will be deployed as a web-based software application that can also be integrated into state and regional project development and planning processes.

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Use of Passenger Rail Infrastructure for Goods Movement

Economic Feasibility Study from California's San Francisco Bay Area

K. Sivakumaran, X. Y. Lu, and M. Hanson

As demand for freight movement rises, so does truck traffic. In turn, traffic congestion, harmful emissions, maintenance costs, and accidents increase. One alternative to truck transport of goods is mixed-goods service on passenger rail networks, a concept that offers several benefits to the involved parties. These benefits include additional revenue for rail operators, more reliable travel times, reductions in harmful trucking externalities, and more efficient usage of existing facilities. As a case study, the use of the Bay Area Rapid Transit (BART) system in California for FedEx Express cargo movement is examined. FedEx Express was selected because the company's major hub is located at Oakland International Airport (OAK). To analyze the potential costs and benefits of BART mixed-goods service, two alternatives are compared against the status quo of truck-only transport. The first alternative assumes minor capital investment; the second assumes far greater capital investment, including a jointly operated BART–FedEx facility at OAK. Truck vehicle miles traveled (VMT), FedEx Express operating costs, BART operating costs, and carbon dioxide emissions are determined for the status quo and each alternative. Analysis shows that given sufficient demand, mixed-goods service can be profitable for passenger rail systems, cost-effective for air freight carriers, and highly effective in reducing truck VMT and associated externalities.

As demand for freight movement increases, so does truck traffic on California's roads. As truck transport grows, so do trucking's associated problems, including traffic congestion, harmful emissions, maintenance costs, and accidents. Thus, there exists an imperative to explore alternatives to truck transport for freight movement, specifically the use of passenger rail systems to move goods. This concept is motivated by potential benefits to all parties. A passenger rail system offering service to both passengers and freight carriers might benefit from (*a*) an additional revenue source, (*b*) more efficient use of its existing capacity, particularly during off-peak periods, and (*c*) a potential source of cross-subsidization, such that revenue from freight service is reinvested in passenger service improvements. The freight carrier, in shifting goods from trucks to rail, can potentially benefit from (*a*) more reliable travel times for goods, particularly during periods of nonrecurrent congestion, (*b*) cheaper transport costs, and (*c*) fewer truck accidents. Society may benefit from reduced truck traffic through reductions in (*a*) harmful greenhouse gas (GHG) emissions, (*b*) truck-induced delays, (*c*) road maintenance costs, and (*d*) other negative externalities such as noise and truck-related accidents.

This feasibility study explores the use of the Bay Area Rapid Transit (BART) system for transport of FedEx Express air cargo. The economic feasibility of such a system is presented from a purely operational perspective. A later report will include the required capital costs, but for the purposes of this paper, capital investments are considered sunk costs. The motivation for doing so is methodological; if mixed-goods service is found to be fiscally infeasible from an operational perspective, then there is no need to examine the required capital expenditure.

The paper is structured as follows. The first section describes the critical characteristics of the system under analysis. The next section outlines the assumptions and methodology of the economic feasibility model. The model examines three different operational scenarios: the status quo of truck-only transport, an alternative requiring minor capital expenditure (Alternative A), and an alternative requiring significant capital expenditure (Alternative B). The final sections discuss the quantitative results of the economic feasibility study and describe how this type of service might be further investigated.

SYSTEM CHARACTERISTICS

This section describes the characteristics of the system under analysis, specifically that of the major passenger rail operator in the Bay Area, BART, as well as one of the area's major air freight carriers, FedEx Express. These two parties have unique capabilities and restrictions that must be considered when developing an accurate cost–benefit analysis.

Characteristics of the BART System

BART is the Bay Area's primary passenger rail transit system, connecting more than 26 cities across four counties. Construction began in 1964, and the system now has over 104 mi of track con-

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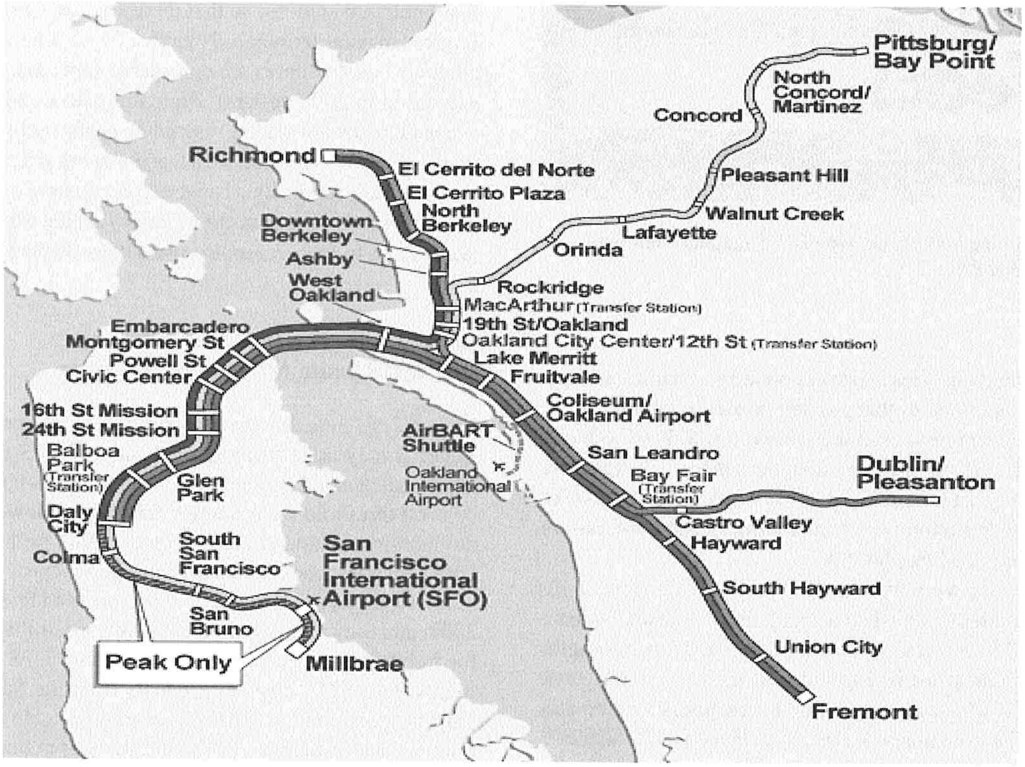

FIGURE 1 BART system map.

necting 43 stations (Figure 1). BART provides five lines of service at headways of approximately 15 min, with a very high on-time reliability of nearly 95%. However, because of the extensive overlaying of lines throughout the system, the frequency of service can be higher during peak periods. Although the current BART system has few sidings to allow for passing, the system does have interchanges at transfer stations that allow trains to travel between any two points seamlessly. The BART system is electrically powered and emits no air pollution.

Unlike many other urban passenger rail systems, BART uses a nonstandard gage of 5 ft 6 in.; the gage most commonly found in the United States is 4 ft 8.5 in. Consequently, the system relies on custom-made rolling stock, with a total of 669 cars. During a typical morning peak-hour commute, 541 cars are in service, while the remainder are used to build spare trains, are in repair, or are involved in other maintenance work. BART cars measure 70 ft × 10.5 ft × 7 ft (length × width × height) and have a load capacity of 30,000 lb. Door dimensions are approximately 4.5 ft × 6.5 ft (width × height). Because of the length of the typical BART station (approximately 710 ft), BART typically does not operate trains longer than 10 cars. BART trains are able to operate in both directions without the need to turn around.

BART has several plans for system expansion, including a track extension of the Fremont line southward to San Jose (scheduled for construction by 2018) as well as renewal of the entire BART fleet beginning in 2016; 700 new cars are expected by 2024. Hypothetically, if a connection between BART and Oakland International Airport (OAK) could be constructed, perhaps supportive of both passengers and freight, a truck transshipment link for one end of the mixed-goods transport chain could be eliminated.

These future projects have the potential to strengthen the viability of BART mixed-goods service. Retired BART cars could be retrofitted and used for freight movement. Furthermore, BART currently uses 30% of its capacity on average for daily passenger movement, with the other 70% unused. Here, the calculated capacity is based on BART's current operation, with 15-min headways and 10-car consists. However, if BART were to adopt modern communication and control systems, the operating headway could be greatly reduced and the capacity doubled or even tripled.

Characteristics of the Air Freight Carrier: FedEx Express

Air freight carriers such as FedEx, DHL, and UPS all have a strong need for high-frequency, reliable, cost-effective transportation chains. With the recent withdrawal of DHL from the U.S. air and ground carrier markets, a significant portion of the carrier market share will likely be assumed by FedEx and UPS, further stressing their existing transport chains. Furthermore, the overall market volume is expected to increase with the growing number of imports from rapidly emerging regions such as the Pacific Rim.

FedEx Express, an operating unit of FedEx, presents itself as a particularly promising participant in an economic feasibility study because of its strong presence in the Bay Area. The FedEx Western Regional Hub at OAK acts as a sorting and distribution center to seven states on the West Coast. Smaller distribution centers are scattered throughout the Bay Area in cities such as Concord, Dublin, and San Jose. FedEx Express also maintains flights to and from the San Francisco International Airport (SFO). As traffic congestion

FIGURE 2 FedEx long-haul truck, type CTV5 (unpublished data, Michael Graham, FedEx).

increases along the Bay Area's urban corridors, FedEx has been exploring service alternatives that provide greater reliability.

All FedEx container types, other than standard U.S. Postal Service (USPS) containers, are transported throughout the FedEx transport chain using casters; that is, containers are not forklifted onto trucks but rather slid across platforms and aboard trucks using the casters mounted throughout loading platforms.

FedEx utilizes two truck types, CTV4 and CTV5 (Figure 2), which differ in length (unpublished data, Michael Graham, FedEx). The CTV4 and CTV5 trucks measure 45 ft and 53 ft in length, respectively. Both measure 10.5 ft wide. As mentioned, the truck beds are retrofitted with casters to allow for seamless loading and unloading of FedEx containers. FedEx containers operate within a closed loop for security purposes; that is, once a container is initially filled and closed prior to distribution, it remains closed until it reaches its final local sorting center.

FedEx Express demand is time dependent. FedEx Express packages originating from locations outside the Bay Area and destined for the Bay Area are distributed in the morning between 3:00 a.m. and 7:00 a.m. FedEx Express packages originating from the Bay Area and destined for locations outside the Bay Area are collected between 5:00 p.m. and 9:00 p.m.

MODEL ASSUMPTIONS AND METHODOLOGY

This section outlines the assumptions used for this economic feasibility study.

Case Study Alternatives

This analysis examines two alternatives for BART mixed-goods service over the 20-year period between 2021 and 2040. Both will be compared against the status quo, in which only trucks are used for transport of FedEx products. Alternative A will consider a scenario in which minor capital investment is required: only existing BART yards, maintenance areas, and those stations with adequate room for nearby expansion (Milpitas and Dublin–Pleasanton) will be used as FedEx transfer terminals. Note that Alternative A requires FedEx truck transshipments at both ends of the transport chain. For Alternative B, a jointly operated BART–FedEx facility at the FedEx Oakland Regional Hub is assumed, which would require a connection between OAK and the existing BART network. If BART freight trains could be accommodated along this connection, a truck transshipment link could be eliminated. Similar to Alternative A, Alternative B also includes sufficient capital investment for retrofitting of existing BART stations, including the Glen Park and South San Francisco stations, so that these stations can operate as FedEx Express transfer terminals. Note that for all alternatives, only operating cost expenditures are considered (note also that all costs are expressed in 2008 dollars). Both alternatives will require capital expenditure toward loading–unloading platforms for containers, stripping and retrofitting BART cars, and making other station modifications to ensure segregation between passengers and FedEx containers. A future study will outline the necessary capital expenditures for both alternatives to fully determine overall economic feasibility.

Exclusive Rights by FedEx Express to BART Goods Movement Services

This analysis considers the transport of FedEx Express products only. Benefits may arise from the inclusion of UPS products because additional demand sources could lead to the surpassing of a critical demand threshold for economic feasibility. However, considering this additional demand source would require further inspection into UPS container types and handling requirements.

Interestingly, UPS actively participated in feasibility studies in 2008, and they maintain interest in the possibility of using BART for freight movement, particularly because UPS does not operate flights from SFO; all UPS products from the San Francisco area must be transferred to OAK for air transport. However, because of limited data availability, economic analysis at this stage will focus on FedEx Express products.

Locations

A simple graphical depiction of the network for each alternative is shown in Figures 3 and 4. There are six FedEx Express distribution centers in the Bay Area (listed in the key to the figure) that are located near the following existing or future BART facilities: Concord, downtown San Francisco, Dublin, Hayward, Milpitas, Oakland, and South San Francisco. The BART Milpitas station is scheduled for construction in 2018. The lone exception is Node 4b in Alternative A; there is no BART station at this location, but there is a small BART maintenance facility known as the Oakland Annex Shop where there is a spur track and adequate room for truck loading and offloading. Node 4ab acts jointly as a BART station and FedEx center in Alternative B.

BART stations such as Colma, Union City, and Concord are of particular interest because of their proximity to BART maintenance yards, which are completely separated from passenger movements. These nearby yards will behave as "depots" for freight consists in Alternatives A and B, meaning that all trains must be assembled in one of these yards before serving a particular route. Furthermore, while some node names correspond to BART station names, the nodes themselves correspond either to BART yards or loading facilities built in proximity to existing stations. Segregating passenger and freight movements will help mitigate both station congestion and conflicts between passenger and freight consists, which could otherwise be problematic during peak ridership hours.

Demand

An origin–destination (O-D) demand matrix has been developed through communication with FedEx Express but is scaled so that

Symbol	Description
□	BART Transfer Point
○	BART Station
●	FedEx Distribution Center
———	BART Link
- - - - - -	Truck Transshipment Link

FedEx Acronym	Distribution Center Location
RHV	San Jose
HWD	Hayward
LVK	Dublin
OAK	Oakland Airport Hub
CCR	Concord
SFO	Downtown San Francisco
SQL	South San Francisco

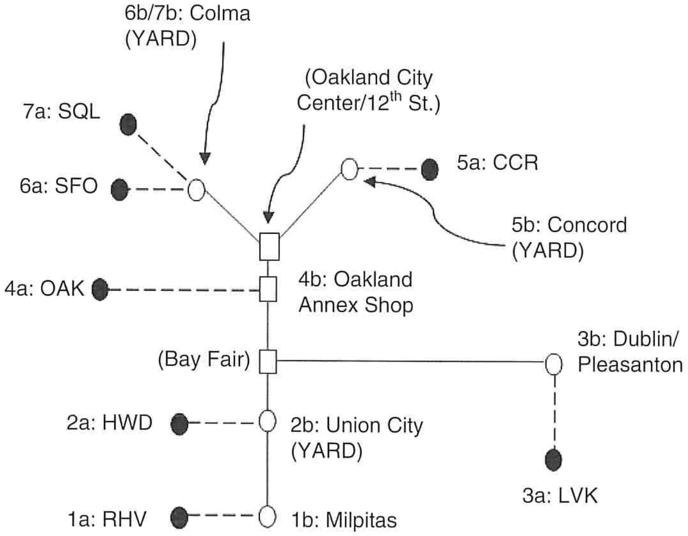

FIGURE 3 System network under consideration for Alternative A.

true demand is not disclosed (for proprietary reasons). This matrix, shown in Table 1, roughly conveys the assumed daily demand in pounds across the given locations for 2009. A demand growth rate of 5% per year is also incorporated to account for the expected future increase in goods movement. This growth rate value was determined using the Metropolitan Transportation Commission's (MTC) future estimates of Bay Area air cargo demand (*1*).

Demand patterns follow the time windows mentioned previously, in which all distribution takes place during the morning period and all collection takes place during the afternoon period.

Container Type

Note that FedEx containers (other than USPS containers) would not be able to (*a*) fit through existing BART car doors or (*b*) be transported via BART, because the containers require caster decks for movement. Thus, rather than completely retrofitting BART cars to fit all FedEx container types, which could be prohibitively expensive, it may be more reasonable to consider transport only of USPS containers using modified BART cars. USPS containers measure 5.75 ft × 3.5 ft × 5 ft (length × width × height). A load density of 5.5 lb/ft^3 is assumed, which is roughly equivalent to the average load density of most existing FedEx container types (unpublished data).

Vehicle Types and Capacities

All FedEx trucks are assumed to be of type CTV5 for analysis (Figure 2). Truck capacity is constrained both by container shape and weight; under these two constraints, trucks have a capacity of 16 USPS containers.

All BART freight cars are assumed to be bidirectionally operable "C" cars, which should be available for use after BART begins its fleet overhaul in 2016. These cars could be stripped of seating and fitted with locking mechanisms for wheeled USPS containers. A single BART freight car, when considering container weight and shape and doorway dimensions, can hold 24 USPS containers.

Note that if trucks and BART cars were completely packed with containers, they would be able to carry 24 and 36 containers, respectively. However, some room must be provided within vehicles for access to containers. Finally, although consolidation is the aim, vehicles may have to leave their origin before being completely filled because of delivery time constraints. Thus, slightly reduced capacity constraints are used.

Empty Container Returns

Empty container returns must also be considered, because the demand O-D table is likely to be unbalanced (Table 1). The number of empty

Symbol	Description
□	BART Transfer Point
○	BART Station
●	FedEx Distribution Center
◍	Joint BART/FedEx Distribution Center
———	BART Link
– – – – – –	Truck Transshipment Link

FedEx Acronym	Distribution Center Location
RHV	San Jose
HWD	Hayward
LVK	Dublin
OAK	Oakland Airport Hub
CCR	Concord
SFO	Downtown San Francisco
SQL	South San Francisco

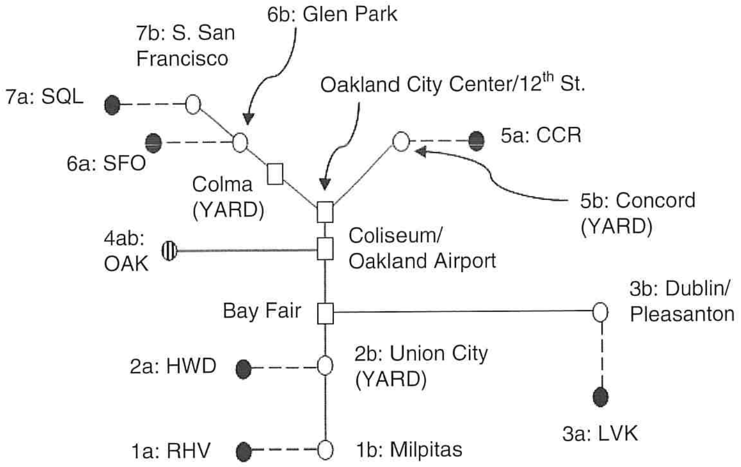

FIGURE 4 System network under consideration for Alternative B.

containers that must be transported to or from a given location is simply the difference between the location's outgoing and incoming demand.

Freight Car Storage Areas and Empty Train Travels

For Alternative A, it is assumed that there is no storage space for BART cars at the Oakland Annex Shop; thus, all freight consists must be assembled at one of BART's four yards before leaving for a particular route. During morning operations, because all movement is from OAK, the yard near Union City (Node 2b) is assumed to supply freight consists to the Oakland Annex Shop station. After unloading all goods at the final destination, the empty train will depart for the nearest yard. During afternoon operations, each route's origin (Node 1b, 3b, 5b, 6b–7b, or 7b) will have trains supplied from the nearest yard. After unloading goods at OAK, each empty train will return to Node 2b. However, a new train must then be assembled that returns empty containers to a given location (trains may be either originating from or destined for OAK). Empty container returns help ensure that the same number of freight cars will be in each yard at the beginning of each day.

For Alternative B, it is assumed that there is adequate BART car storage at the FedEx–BART facility (Node 4ab). Thus, this facility will assume the role played by Node 2b in Alternative A. All other procedures from Alternative A are adopted for Alternative B.

Link Travel Times

In order to determine the operating costs incurred for BART cars, the travel times across the system network must be established. Since it is not feasible for a single train to transport all goods throughout the network because of delivery time constraints, particular routes have been assigned for freight trains, as seen in Table 2. Route travel times were approximated from BART schedules (*2*). However, those times

TABLE 1 Origin–Destination Demand Matrix (lb)

	1a: RHV	2a: HWD	3a: LVK	5a: CCR	6a: SFO	7a: SQL
4a: From OAK	36,600	27,600	25,800	26,400	51,000	31,800
4a: To OAK	120,000	43,800	198,000	102,000	153,000	72,000

NOTE: RHV = San Jose; HWD = Hayward; LVK = Dublin; CCR = Concord; SFO = downtown San Francisco; SQL = South San Francisco.

TABLE 2 BART Travel Times for Alternatives A and B

Route	Route Travel Time (h)	Total Service Time (h)
Alternative A		
1b ←→ 2b ←→ 4b	0.66	1.33
3b ←→ 4b	0.51	1.34
5b ←→ 4b	0.52	0.92
6b/7b ←→ 4b	0.56	0.96
Alternative B		
1b ←→ 2b ←→ 4ab	0.66	0.93
3b ←→ 4ab	0.46	0.90
5b ←→ 4ab	0.65	0.65
7b ←→ 6b ←→ 4ab	0.72	0.77

include the dwell times across intermittent stops; thus, an assumed 40-s dwell time per stop has been subtracted from the provided trip times. Furthermore, the aforementioned empty train travel times (from and to the yards corresponding to the beginning and end of a particular route) should be added to all route travel times in order to calculate the true cost of service. The resulting total service times, as well as the route travel times, are given in Table 2.

It is also necessary to determine the link travel distances and times across the road network for truck transport of FedEx goods. Travel distances for all links are determined according to the locations of BART stations and FedEx distribution centers. These distances are listed in Table 3. While it can safely be assumed that transshipment travel times between local FedEx distribution centers and BART stations will remain constant, the line-haul travel times in the status quo might be expected to change over time as a result of rising freeway demand and the subsequent reduced travel speeds. Thus, this analysis uses the predicted interregional travel speeds provided by the MTC (*3*).

TABLE 3 Truck Travel Distances for Various Alternatives

Link	Truck Travel Distance (mi)
Status Quo	
4a ←→ 1a	33.1
4a ←→ 2a	15.5
4a ←→ 3a	20.9
4a ←→ 5a	31.6
4a ←→ 6a	22.4
4a ←→ 7a	28.6
Alternative A	
1b ←→ 1a	3
2b ←→ 2a	4
3b ←→ 3a	3.6
5b ←→ 5a	4
6b/7b ←→ 6a	8.6
6b/7b ←→ 7a	4.9
4a ←→ 4b	8.8
Alternative B	
1b ←→ 1a	3
2b ←→ 2a	4
3b ←→ 3a	2.6
5b ←→ 5a	4
6b ←→ 6a	3.8
7b ←→ 7a	3.4

Handling

A handling time of 0.025 h (1.5 min) per container is assumed. This handling time is defined as the time needed to move one container from a BART car across a station platform and secure the container onto a FedEx truck (and vice versa). Compared to the status quo, Alternative A will require two additional handling movements (one movement at all BART stations connected to local distribution centers and one movement at Node 4b), and Alternative B will require one additional handling movement (at all BART stations connected to local distribution centers). Total handling cost is given by the product of the handling time per container, the number of containers handled, the number of handling movements, and the hourly handling costs. Regardless of how responsibility is allocated for loading and offloading items at BART stations, BART must still incur some labor cost during handling movements, because BART operators will be standing by as trains are loaded and offloaded. Similarly, FedEx truck operators will be on standby while trucks are offloaded and loaded. Therefore, the total handling time cost is assumed to be incurred by both FedEx and BART.

Truck VMT Estimation

The number of trucks required between any two points can be approximated as

$$n_{ij} = \frac{D_{ij}}{K}$$

where D_{ij} = demand (containers) originating from location i and destined for location j, and K = truck capacity (containers). The demand matrix provided earlier can thus be converted into a truck trips matrix. From the number of truck trips, the annual truck VMT, external social costs, and total truck operating costs can be calculated for each alternative. All trucks are assumed to travel round trip.

External and Social Costs

Four major external costs can arise from heavy-duty truck VMT: congestion and delay costs, emissions costs, accident costs, and infrastructure–maintenance costs.

The delay savings that arise from reduced truck VMT are difficult to estimate, given that the savings depend on the freeway's total demand. Although there may be some delay reduction from the proposed mixed-goods service, no quantification of these savings is included here.

To quantify reductions in GHG emissions, a carbon dioxide (CO_2) emissions rate of 22.2 lb/gal is used for diesel fuel (*4*). A constant heavy-truck fuel economy of 10 mpg has been assumed over the analysis period.

With truck VMT reduced, the number of freeway accidents will likely be reduced. To quantify this cost, a truck accident rate is used. This rate is derived from 2006 statistics for the United States (*5*). The average cost of all heavy-truck accidents in 2005 was $91,112 (*6*).

The annual accident cost is given by the product of these two factors together with the annual truck VMT. Half of this resulting cost is allocated to FedEx annual operating cost, and half to society.

The road damage unit cost due to urban truck travel is taken as \$0.074 per truck mile (*7*).

Operating and Labor Costs

Heavy-duty truck operating cost per mile was given as \$3.28/mi in an unpublished report by Rohit Rai (whose previous work is continued in this study), but because this per-mile cost included driver costs, a lower value of \$2.70 is used so that the per-mile trucking cost includes only fuel, maintenance, and ownership–depreciation costs. The diesel fuel cost component is assumed to follow the same trend as gasoline costs, rising to roughly \$7.50/gal by 2035 (*8*). The per-hour cost includes FedEx driver wages, taken as \$22/h, and employee benefits such as health insurance and worker's compensation, leading to an hourly cost of \$31 (*9, 10*). Hourly handling labor cost is assumed to be the same as FedEx driver costs (\$31/h). Other components of driving cost include the \$11.25 bridge toll for trucks, a \$0.25/mi congestion charge, and a carbon tax on all VMT that would increase the cost of driving by 20%. All of these charges are expected to be implemented by 2035 in the Bay Area (*3*). The congestion charge is applied only to the freeway travel component of each truck trip, and the bridge toll only to those trucks that use links 4a←→6a and 4a←→7a in the status quo, as only these two links require travel across the Bay Bridge.

Difficulties arise in approximating BART operating cost because of data limitations. Through communication with BART's Financial Planning Office, an operating cost of \$250/car hour was obtained. This value is simply the total annual operating cost divided by the total annual car hours (*11*). However, the operating cost for trains, which possess economies of scale, is required. Therefore, rather than directly applying the given operating cost per car hour, the following methodology is applied for cost estimation. First, given that BART trains range from two to 10 cars in length, the average train length is assumed to be six cars. Multiplying the hourly operating cost for cars by this length, an hourly operating cost of \$1,500/h is obtained for a six-car train. Further assuming that BART freight trains will not require the same amenities as BART passenger trains (e.g., lighting and air conditioning), a reduced operating cost value of \$1,250/h is used for a six-car train. Because the relationship between train length n and cost should show economies of scale, it is further assumed that the hourly operating cost can be expressed as the concave function $1000n^{1/8}$, where $2 \leq n \leq 10$. Using this function, the hourly freight train operating cost ranges from \$1,090 for a two-car train to \$1,330 for a 10-car train.

Total BART train hours are determined similar to total truck VMT. The number of BART cars required is given simply by

$$n_k = \frac{D_k}{K_{\text{BART}}}$$

where D_k = demand (containers) for route k, and K_{BART} = BART car capacity (containers). From the number of cars required, the number of trains required can be determined by dividing the required number of cars by the 10-car limit. The appropriate operating cost rate, according to the cost function above, is then assigned to the required trains and their respective lengths. A single train's daily operating cost is given by the product of its hourly operating cost and its total time in service. The annual operating cost is found by summing the operating cost over all trains and working days for the year.

Security

All FedEx goods, once containerized at their origin distribution center, are not opened until reaching their destination distribution center. Furthermore, all FedEx goods leaving the Oakland Regional Hub must pass through airport security. Thus, it is reasonable to assume that FedEx containers, which already meet stringent airport security requirements, will satisfy any requirements imposed by BART.

RESULTS

Figure 5 shows the annual net benefit (undiscounted) curves for Alternatives A and B, in comparison with the status quo. Here, net benefit is taken as the difference between the total operating cost of the status quo and the given alternative. A negative level of net benefit indicates a need for subsidies; when net benefit is positive,

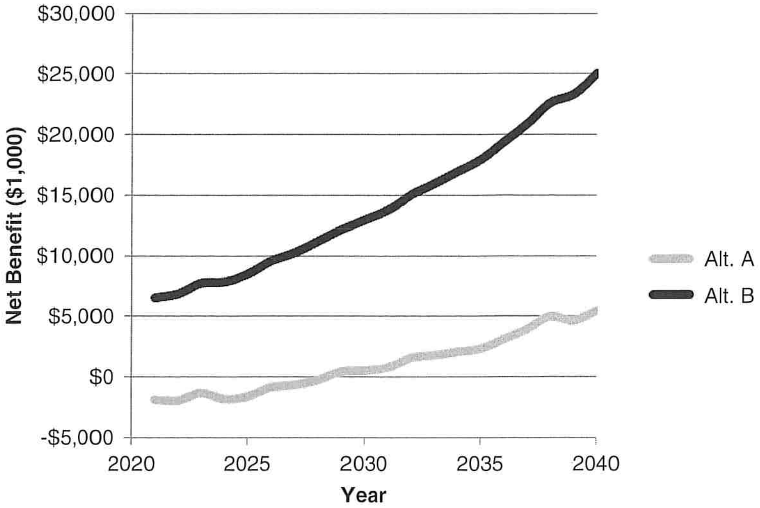

FIGURE 5 Net benefit curves for Alternatives A and B, compared with status quo.

opportunities arise for BART profits and FedEx savings. The exact levels of profit for BART and savings for FedEx would simply depend on a mutually agreed-upon price for transported containers.

For Alternative A, which requires minor capital investment, some subsidy is required throughout some of the timeline. Nevertheless, beyond 2030, the simulation suggests that mixed-goods service can become profitable and can remain that way as container demand grows. Note, however, that additional parametric analysis showed the feasibility of Alternative A to be highly dependent on the assumed handling time per container; if this time is too high, the net benefit will actually decrease with increasing demand. Furthermore, tremendous savings in truck VMT can be achieved; the cumulative truck VMT savings over the analysis period amounts to nearly 60 million VMT. This translates to nearly 60,000 metric tons of CO_2 emission savings, as well as nearly \$5 million in accident savings and more than \$4 million in maintenance savings.

For Alternative B, which requires significant capital investment but eliminates one of the transshipments required in Alternative A, even greater savings in truck VMT are achieved. The cumulative VMT savings amount to nearly 100 million VMT, which translates to roughly 100,000 metric tons of CO_2 emission savings. Accident and maintenance savings totaled more than \$8 million and \$7 million, respectively. In addition, no subsidy is ever required for Alternative B. Thus, if container demand is sufficient, mixed-goods service can be profitable for BART and beneficial for FedEx from solely a fiscal perspective. Assuming a discount rate of 5%, the accumulated total cost savings, in comparison with the status quo, amounts to nearly \$100 million. Some of these savings could be channeled toward recovery of the initial capital investment, as well as toward improvements in passenger service, which might further incentivize transit ridership. Note that a clear trend is established in the results: the higher the demand level, the more profitable mixed-goods operation becomes.

Other social benefits could be expected that are not included in this analysis, such as reductions in noise and particulate matter. Furthermore, improvements to BART, such as sidings for train bypass and adoption of new control technologies, could benefit both freight carriers and passengers by increasing system capacity and reducing travel time. Such improvements might stimulate additional transit ridership. Government agencies must weigh all potential benefits against any required subsidies and start-up costs to determine whether mixed-goods service merits financial support.

CONCLUDING REMARKS

This economic feasibility study shows significant promise for exploring the possibility of mixed-goods service on passenger rail systems. Both service alternatives show a trend suggesting that the higher the demand, the lower the level of subsidy required. Furthermore, with sufficient demand and significant capital investment, the passenger rail system can actually derive profit from such service, while the air freight carrier can derive savings. These findings should motivate researchers to investigate how other potential demand sources might be exploited so that mixed-goods service can become both profitable and environmentally sustainable.

Several future extensions to this study will be pursued. The government might not be willing to fully cover the tremendous capital expenditures required for Alternative B for a service that might primarily benefit a single private company (such as FedEx). Thus, developing a valid estimate of initial capital and other start-up costs is critical, so that all future benefits can be discounted and compared against the full project cost. Furthermore, the assumed level of infrastructure investment can greatly influence certain components of freight service, such as handling time at transshipment points.

Future studies should also investigate the logistical barriers inherent in mixed-goods service, including noninterference with existing passenger transport operations and routine maintenance activities. For example, because morning freight service would fall outside current BART operating hours, analysis should also consider the additional overhead and logistical costs required during this time period.

Researchers might also incorporate latent demand, perhaps by assuming that cars fill the available road space left by the removal of trucks from freeway corridors; doing so would provide a more valid estimate of social benefits. For the preceding analysis, latent demand was assumed to be negligible because the daily truck flows were found to utilize a marginal percentage of freeway capacity (approximately 1%).

Other elements not yet included might prove beneficial to mixed-goods service. One such critical element is the inclusion of other freight carriers besides FedEx as BART customers. Overlaps in demand patterns across different customers could lead to even greater economies of scale for BART freight transport, particularly in comparison with truck transport. These additional demand sources in the Bay Area might include UPS containers, agricultural produce, and containerized or noncontainerized products from the Port of Oakland. Moreover, tailoring BART service to just a single customer may be risky, given that DHL, a company similar to FedEx, recently ceased service within the Bay Area. Thus, any mixed-goods service providers should attempt to accommodate several different sources of freight demand. However, additional costs might arise when accommodating different demand sources because of variations in container characteristics and service requirements. Another element not quantified here is the higher level of reliability afforded by rail transport in comparison to truck transport. Including this benefit for freight carriers may further skew the results in favor of mixed-goods service.

This paper does not necessarily intend to make a case for implementation, but rather for continued analysis of mixed-goods service. The results of this economic feasibility study make a strong case for future research in this area. The results should be of particular interest to other urban areas across the United States where passenger rail systems exist in proximity to major air freight terminals, such as Chicago, Los Angeles, New York, and Washington, D.C. Some of these systems may have characteristics that favor mixed-goods movement, such as intermodal transfer stations, containers that can move between different modes, and standard-gage rails.

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The Intermodal Freight Transport Committee peer-reviewed this paper.

Modeling and Performance Assessment of Intermodal Transfers at Cargo Terminals

Cheng-Chieh (Frank) Chen and Paul Schonfeld

This study develops an analytical model for coordinating vehicle schedules and cargo transfers at cargo terminals to improve system operational efficiency and minimize total system costs. The studied problem is formulated as a multihub, multimode, and multicommodities network problem with nonlinear time value functions for shipped cargo. This is done primarily by optimizing service frequencies and slack times for system coordination while also considering loading and unloading, storage, and cargo processing operations at the transfer terminals. In a series of case studies, the model has shown its ability to determine optimal service frequencies (or headways) and slack times based on given inputs. Numerical results are solved using sequential quadratic programming and a genetic algorithm.

Increasing awareness that globalization and information technology affect the patterns of transport and logistic activities has increased interest in the integration of intermodal transport resources. This study develops an intermodal timed transfer model to coordinate vehicle schedules and cargo transfers at cargo terminals to improve system operational efficiency and minimize total system costs. The term "intermodal" has been used in many applications that include passenger and freight transportation. For the purpose of this paper, intermodal freight transport is defined as the use of two or more modes to move a shipment from origin to destination and involves physical infrastructure, goods movement and transfer, and other relevant activities under a single freight bill (*1*).

Most operations at intermodal freight terminals require transfer movements from one mode to others to serve cargo with diverse destinations, especially for break-bulk, cross-docking, or transshipment systems. This study focuses on a key intermodal operational issue: How should a timed transfer system be developed for shipments through the intermodal network? A timed transfer system requires a well-defined strategy of schedule coordination; such a strategy can benefit transportation firms, terminal operators, infrastructure providers, shippers, and forwarders. There are many significant advantages provided by integrating multiple transport schedules, such as

1. Eliminating direct routes connecting all origin–destination (O-D) pairs and concentrating cargo on major routes with faster modes (e.g., airplanes) or lower-cost modes (e.g., container ships);
2. Improving the utilization of existing transportation infrastructure;
3. Reducing the requirements for warehouses and storage areas resulting from poor connections; and
4. Reducing other impacts, including traffic congestion, fuel consumption, and emissions.

Several previous studies have considered the schedule coordination problem in transit systems, but few have dealt with intermodal freight transportation. Ceder and Wilson presented a hierarchical model for the whole planning process, network design, headway or frequency setting, and timetable development of bus transit systems (*2*). Abkowitz et al. simulated a variety of dispatching strategies at a timed transfer hub (*3*). Their simulation results on two bus lines show that a no-holding strategy is best when the bus lines have unequal headways and that a holding strategy is preferable when the bus lines have equal headways. Dessouky et al. developed a simulation-based model to demonstrate that technology for communication, tracking, and passenger counting is most advantageous when the schedule slack is close to zero, when the headway is large, and when there are many connecting bus lines (*4*). Domschke coordinated transit schedules based on minimizing users' total transfer waiting time with given operation hours (*5*).

Lee and Schonfeld formulated models for determining optimal vehicle slack times at a transfer terminal serving multiple bus routes (*6, 7*). Stochastic vehicle arrivals were considered while formulating the objective coordinated transfer cost function. Analytical results showed that the standard deviation of vehicle arrival times is an important factor affecting the durations of slack times. Chowdhury and Chien developed a schedule coordination method for a rail transit line and multiple feeder routes connecting at different transfer stations (*8*). The slack times of coordinated routes were optimized by balancing the savings from transfer delays and additional cost from slack delays and operating costs. Zhao et al. presented an analytical model for a schedule-based transit system to determine the optimal slack times that minimize passengers' expected waiting times (*9*). Bruno et al. proposed a schedule optimization model by balancing the operative costs of the service and the passenger waiting time at the transit terminal (*10*). Ting and Schonfeld optimized the headways and slack times jointly to minimize the total costs of operating a multiple-hub transit timed transfer network (*11, 12*). Their results show that for routes with significantly different demand or route length, coordination with integer–ratio headways is preferable to a single common headway. (Having common or at least integer–ratio headways on connecting routes greatly reduces the potential for transfer delays.) These schedule coordination methods are mainly designed for public transit systems and neglect the unique attributes of freight transportation, such as loading and unloading, cargo processing and storage, and shipments with different freight types. In addition, the assumption about the constant value of time of passengers

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used in these papers may not be suitable for some perishable goods. Although some specific characteristics in freight transportation are quite different from those in public transit systems, the conceptual basis for optimizing transfers is fairly similar.

Some studies have addressed the freight schedule optimization problem and coordination issue. Gue developed a trailer scheduling model based on the layout of the terminal to minimize workers' travel distances, which can provide a basis of scheduling coordination between delivery and cargo-processing vehicles within the terminal (*13*). Voss formulated a multicommodity network design problem and solved it with a tabu search algorithm (*14*). Anderson et al. proposed a capacitated multicommodity network design model with multiple fleets' schedule coordination (*15*). Their model determined departure times of the services by minimizing throughput time of the demand in the system.

The main purpose of this paper is to develop a timed transfer system at an intermodal terminal so as to minimize the total system cost by optimizing the service frequencies (or headway), slack times, and loading and unloading operations of all modes and routes. The primary methodology is to a considerable extent adapted from previously developed methods focused on public transportation and airline applications, but it also considers the specific characteristics of intermodal freight logistics (*6, 7, 11, 12*). These include

1. Multihub, multimode, and multicommodity network flows. A multicommodity network approach (which is not used for passenger transportation) is widely used for freight transportation because of its different cargo characteristics. In addition, different modes may have different vehicle sizes, turnover rates, travel speeds, and time, all of which may affect the dispatching frequencies. Three different network configurations are considered: (*a*) single hub, (*b*) multiple hubs, and (*c*) multiple hubs forming a loop with multiple routes. Uniform cargo, multiple commodities with the same time value, and multiple commodities with different time values are analyzed in this paper.
2. Cargo processing and storage issues within the terminal. Different shipping patterns may yield different dwell times for cargo and various spatial requirements for warehouses and storage areas. Even for the cross-docking shipments, cargo still need some temporary storage areas for loading and unloading. Starting from a given demand, lower service frequencies may increase vehicle loads but also increase required cargo storage space. If connections are missed, the extra dwell time and storage requirements are also considered.
3. Nonlinear time value functions for perishable cargo. Most previous studies have assumed that passengers' time value varies linearly with time; however, some cargo (e.g., perishable goods, high-technology products, spare parts, shortage of inventories, holiday gifts) may have nonlinear time value functions. The model used here assumes that the value of time of cargo may decrease over time; for example, according to a continuous nonconvex piecewise linear function or a nonlinear probabilistic time value function.
4. Cargo loading and unloading operations. Service frequencies affect vehicle loading and unloading quantities and times. Such issues are usually neglected in transit-related studies; however, these operations may significantly affect the system performance and should be considered in the models.

The remainder of this paper is organized as follows: the optimization problem is described in detail. Multiple commodities with different time value functions are discussed. Some mathematical formulations describing the optimized scheduling coordination problems are introduced and illustrated. Applications of the above models are presented with a series of numerical examples. The paper concludes with a discussion of possible future research.

SCHEDULE COORDINATION OPTIMIZATION PROBLEM AT INTERMODAL TERMINALS

This paper seeks to optimize service frequencies and slack times jointly for routes from one or more modes connecting at intermodal freight terminals in order to minimize the total system cost of operating an intermodal logistic network. The routes and terminal locations within the network are predetermined. All demand information is given and is assumed to be deterministic and uniformly distributed during the specified time periods. The problem is formulated as a multihub, multimode, and multicommodity network. Procedures for optimizing the schedule coordination plan are specified in Figure 1.

Additional assumptions are addressed in the following subsections, which analyze uncoordinated operations, coordinated operations with a common service frequency (or its reciprocal, headway), and coordinated operations with integer–ratio service headways. Uncoordinated operation means that all modes and routes are optimized independently; other coordination methods are developed for different characteristics and combinations of modes.

Proposed Submodel for Scheduling Uncoordinated Operations

The mathematical model for uncoordinated operation is based on independently optimized schedules for different routes. The objective is to minimize total system costs (C_T), which include delivery vehicle operating cost (C_o), cargo dwell time cost (C_w), loading and unloading cost (C_l), cargo processing cost (C_p), and cargo transfer cost (C_f). Cargo in-vehicle cost is not affected by service frequencies; hence, it is not included in the total system cost function.

Initially, to simplify this problem, constant values of dwell, loading, unloading, and processing time are assumed, and nonlinear cases are approached later. Let G (N, E) denote a directed transportation network where N is a set of nodes and E is a set of links. To simplify the notation, i and j are defined as the arrival and departure routes, respectively; each route contains several nodes and links.

The model is expressed as follows:

$$\text{minimize } C_T = C_o + C_w + 2C_l + C_p + C_f \tag{1}$$

subject to

$$C_o = \sum_i B_i T_i f_i = \sum_i \left(a_i + b_i S_i\right) T_i f_i \tag{2}$$

where

C_o = operating cost of route i,
B_i = unit vehicle operating cost (dollars per vehicle minute),
T_i = round-trip time of route i (minutes), including the layover time,
f_i = service frequencies of route i (vehicles per minute),
a_i = fixed vehicle operating cost of route i (dollars per minute),
b_i = variable vehicle operating cost of route i (dollars per pound minute), and
S_i = vehicle size on route i.

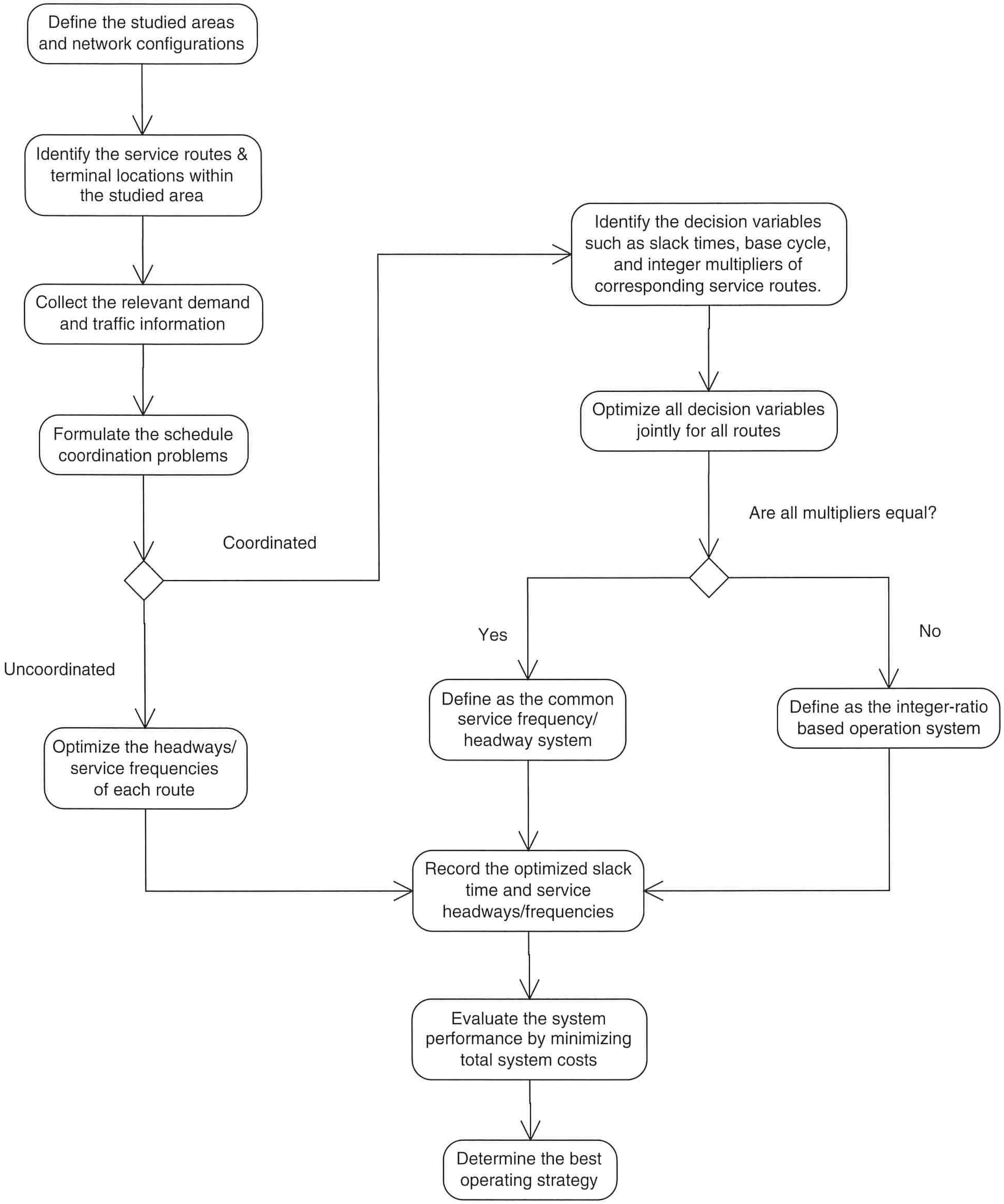

Define the studied areas and network configurations
Identify the service routes & terminal locations within the studied area
Collect the relevant demand and traffic information
Formulate the schedule coordination problems
Coordinated
Uncoordinated
Optimize the headways/ service frequencies of each route
Identify the decision variables such as slack times, base cycle, and integer multipliers of corresponding service routes.
Optimize all decision variables jointly for all routes
Are all multipliers equal?
Yes
No
Define as the common service frequency/ headway system
Define as the integer-ratio based operation system
Record the optimized slack time and service headways/frequencies
Evaluate the system performance by minimizing total system costs
Determine the best operating strategy

FIGURE 1 Flowchart for optimizing schedule coordination.

The minimized objective function (Equation 1) is formulated as the sum of the operating cost of delivery vehicles, the dwell–loading–unloading–processing time costs of cargo, and transfer cost from a particular transfer terminal to feeder routes. In Equation 2, the operating cost of route i is the product of the required fleet size and the unit operating cost. Equation 3 specifies that the total demand of route i includes m types of cargo. D_i = demand along the route i (pounds per minute).

$$D_i = \sum_m D_i^m \tag{3}$$

Equation 4 expresses the sum of the total dwell time cost of cargo and the corresponding loading time cost along route i. Let μ = unit cargo time cost (dollars per pound minute), w_i = dwell time on route i, θ = unit cargo loading–unloading time (minutes), and σ_i^2 = variance of service headways of the route i (minutes squared). Assuming that shipped cargo arrive at the local freight collection station randomly and uniformly over time, the stochastic dwell time (w_i) can be estimated as Equation 5 (*16*). Equation 6 expresses the sum of total unloading cost of cargo, and the corresponding cargo processing cost from the route i, where ψ = unit cargo processing time (minutes). This assumes the total cargo unloading time is equal to the total cargo loading time.

$$C_w + C_l = \sum_i \mu\left(D_i w_i + \theta S_i l_i\right) = \sum_i \mu D_i\left(w_i + \frac{\theta}{f_i}\right) \tag{4}$$

$$w_i = \frac{1}{2E\left(f_i\right)} + \frac{\sigma_i^2 E\left(f_i\right)}{2} \tag{5}$$

$$C_l + C_p = \sum_i \mu S_i l_i\left(\theta + \phi\right) = \sum_i \frac{\mu\left(\theta + \phi\right)D_i}{f_i} \tag{6}$$

Equation 7 indicates the transfer costs incurred by the transfer demand from route j to i at the transfer terminal k.

$$\begin{aligned} C_f &= \sum_k \sum_m \sum_j \sum_{i,i\neq j} \mu\left(q_{ji}^{mk} w_i\right) \\ &= \sum_i \mu R_i\left(\frac{1}{2E\left(f_i\right)} + \frac{\sigma_i^2 E\left(f_i\right)}{2}\right) \end{aligned} \tag{7}$$

where

C_f = transfer cost along the route i,
q_{ji}^{mk} = amount of freight of type m transferred at intermodal terminal k to route i, and
R_i = total transfer demand to route i.

Equation 8 expresses the summation of travel times of all the links α along the route i. $E(t_\alpha)$ = the expected travel time on link i. Equation 9 expresses the transfer cargo's conservation relations at terminal k.

$$T_i = \sum_{\alpha\in E} E\left(t_\alpha\right) \tag{8}$$

$$\sum_j q_{ij}^{mk} = \sum_i q_{ij}^{mk} \tag{9}$$

Equation 10 assumes that the required storage areas for the total transfer demand cannot exceed the available storage areas at the transfer terminal k. ϵ = unit cargo storage areas; A^k = the available storage areas at transfer terminal k.

$$\left(\sum_i \frac{R_j}{f_i} + \sum_j \frac{R_i}{f_j}\right)\epsilon \le A^k \tag{10}$$

Equation 11 states that the service frequency on any feeder route i should not exceed the maximum allowable service frequency ($f_{\max}$), where N_i = the total available vehicles for dispatching on route i (vehicles), and l_i = the load factor on route i.

$$f_i \le f_{\max} = \frac{N_i}{T_i} \tag{11}$$

Equation 12 states that the service frequency on any feeder route i should exceed the minimum acceptable service frequency ($f_{\min}$).

$$f_i \ge f_{\min} = \frac{D_i}{S_i l_i} \tag{12}$$

Submodel for Scheduling a Coordinated Operation with Common Service Frequency

The main differences between the uncoordinated and coordinated systems are the slack times, which are additional decision variables within the proposed submodels. For the uncoordinated system, the cost terms are related to the service frequency (Equations 2–7). Because the exact vehicle travel and arrival times are uncertain, adding some reserve or "slack" time into the schedule can provide better adherence to scheduled departures at the transfer terminal and allow a better response to demand fluctuations, congestion, and other contingencies. However, increasing slack times in schedules obviously increases scheduled round-trip times for vehicles. For a coordinated operation, the costs of vehicle operation and cargo dwell, loading, unloading, and processing are the same as those for an uncoordinated system. However, some costs related to the transfer movements are sensitive to the slack times and service frequencies. These cost components are formulated in Equations 13 through 16.

$$C_f = C_s + C_m + C_d \tag{13}$$

Equation 13 states that the transfer cost of the coordinated operation with a common service frequency includes three cost components: the slack time cost (C_s), the missed-connection cost (C_m), and the connection delay cost (C_d).

$$C_s = \sum_m \sum_i \sum_{k\in N}\left[\mu\left(H_i^{mk} + F_i^{mk}\right) + B_i f_i\right] s_i^k \delta_i^k \tag{14}$$

where

H_i^{mk} = amount of m types of cargo already loaded at terminal k on route i (cargo per minute),
F_i^{mk} = amount of m types of cargo transferred at terminal k from other routes to route i (cargo per minute),
s_i^k = slack time at transfer terminal k on route i (minutes), and
δ_i^k (binary variable) = 1 if transfer terminal k is located on route i and 0 otherwise.

The slack time cost includes the induced cost for loaded cargo and additional operation cost during the slack time. In Equation 14, the first term is the slack time delay cost for the cargo already loaded in vehicles serving route i, the second term is the dwell time cost for cargo transferred to route i, and the third term is the additional vehicle operating cost resulting from the slack time. Assuming that vehicles do not wait for other vehicles that arrive behind schedule, the missed-connection cost (C_m) is expressed as

$$C_m = \sum_{m} \sum_{k\in N} \sum_{j\in E} \sum_{\substack{i\in E \\ i\neq j}} \mu q_{ji}^{mk} \delta_i^k \delta_j^k \times f_m\left(t_i, t_j\right) \tag{15}$$

Various probability distributions may be used for the travel time and arrival time random variables. Here, the normal distribution is preferred to express them, and vehicle arrivals are assumed to be independent among routes. The missed-connection cost can be expressed by the joint probability distributions for vehicle arrival on any coordinated pair of routes (i, j). Two cases are considered: (a) the feeder vehicle on the route j arrives late, and the receiving one on the route i is not late; and (b) both vehicles are late, but the feeder vehicle arrives after the receiving one leaves. Figure 2a shows the joint probability of missed connections [i.e., $f_m(t_i, t_j)$] for transfer cargo on some particular pair of routes, where $f(t)$ = the probability density function of arrival time.

The connection delay cost can also be expressed by the joint probability distributions for vehicle arrival on any coordinated pair of routes (i, j). Two cases are considered in this cost component: (a) the feeder vehicle on the route j arrives early, but the receiving one on the route i is late; and (b) both vehicles are late, but the feeder vehicle arrives before the receiving one leaves. Figure 2b shows the joint probability of connection delay [i.e., $f_d(t_i, t_j)$] for transfer cargo on some particular pair of routes, and Equation 16 represents the corresponding cost.

$$C_d = \sum_{m} \sum_{k\in N} \sum_{j\in E} \sum_{\substack{i\in E \\ i\neq j}} \mu q_{ji}^{mk} \delta_i^k \delta_j^k \times f_d\left(t_i, t_j\right) \tag{16}$$

Submodel for Coordinated Operation with Integer-Ratio Service Headways

As mentioned by Ting and Schonfeld, the common service frequency is not efficient when the demands or lengths of different routes vary (*12*). Especially for the international intermodal freight transportation network, the characteristics of routes and modes are significantly different. Thus, the concepts proposed by Ting and Schonfeld for coordinating operations with integer ratios for headways and segment travel times are adapted here and revised as follows (*12*). The transfer movements' related cost terms are sensitive to the slack

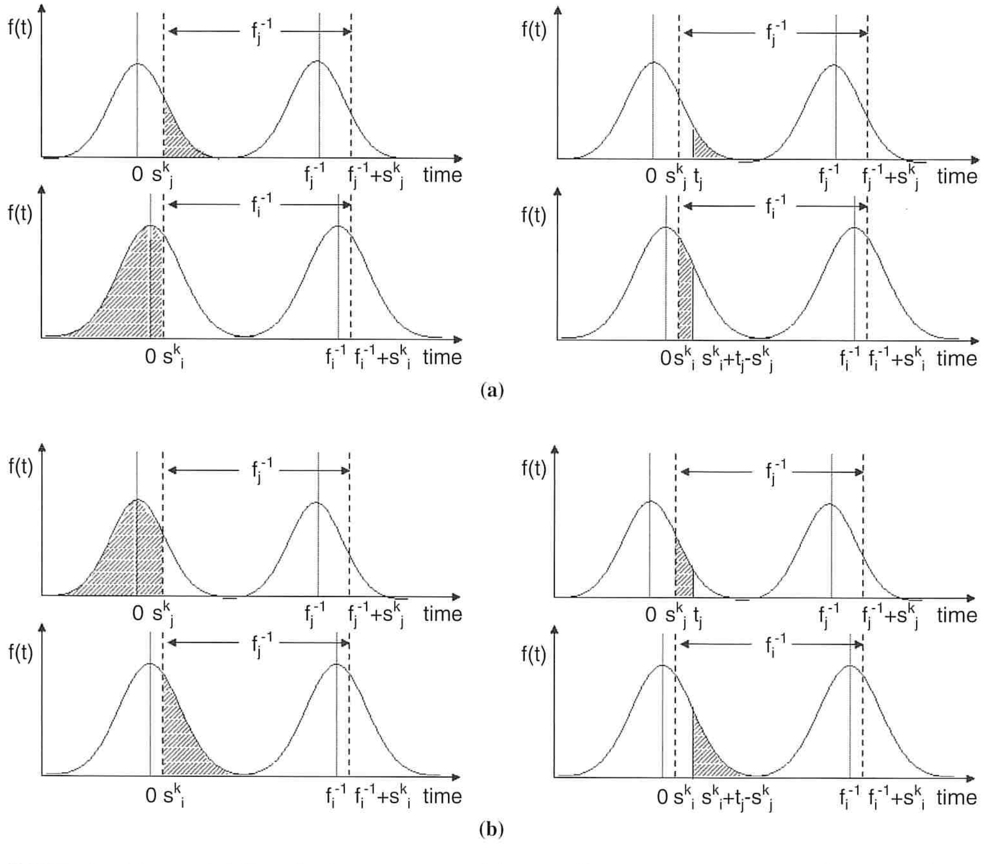


FIGURE 2 Joint probabilities for transfer cargo: (*a*) probability of missed connection from route *j* to route *i* and (*b*) probability of dispatching delay from route *j* to route *i*.

time and service frequency. These cost components are expressed in Equations 17 through 24.

$$C_f = C_s + C_i + C_m + C_d \tag{17}$$

Equation 17 states that the transfer cost of the coordinated operation with integer–ratio service headways (C_f) includes four cost components: the slack time cost (C_s), the intercycle transfer delay cost (C_i), the missed-connection cost (C_m), and the connection delay cost (C_d). The formulation of C_s is the same as for the common frequency method; all other cost terms are as shown in Equations 18 through 21.

$$C_i = \sum_{m} \sum_{k \in N} \sum_{j \in E} \sum_{\substack{i \in E \\ i \neq j}} \mu q_{ji}^{mk} z_{ji}^{mk} \tag{18}$$

$$z_{ji}^{mk} = g_{ji} y \left(\frac{1}{2 g_{ji} y f_i} - \frac{1}{2} \right) + s_i^k = g_{ji} y \left(\frac{h_i}{2 g_{ji} y} - \frac{1}{2} \right) + s_i^k \tag{19}$$

The frequencies and headways of routes i and j can be expressed with integer multipliers (β_i and β_j) of the base cycle y (headway): $h_i = \beta_i y$ and $h_j = \beta_j y$ (or $f_i = \beta_i^{-1} y^{-1}$ and $f_j = \beta_j^{-1} y^{-1}$). Let z_{ji}^{mk} = the average transfer waiting time from route j to route i, and g_{ji} = the greatest common divisor of β_i and β_j. The intercycle cost includes all routes connecting to the transfer center, as shown in Equation 18.

$$C_m = \sum_{m} \sum_{k \in N} \sum_{j \in E} \sum_{\substack{i \in E \\ i \neq j}} \mu q_{ji}^{mk} \frac{g_{ji} y}{h_i} \delta_i^k \delta_j^k \times f_m(t_i, t_j) \tag{20}$$

$$C_d = \sum_{m} \sum_{k \in N} \sum_{j \in E} \sum_{\substack{i \in E \\ i \neq j}} \mu q_{ji}^{mk} \frac{g_{ji} y}{h_i} \delta_i^k \delta_j^k \times f_d(t_i, t_j) \tag{21}$$

In Equations 20 and 21, the missed connection cost (C_m) and the connection delay cost (C_d) are slightly adjusted from those of the common service frequency model. Here, it is assumed that shipments missing their scheduled connection can always be carried on the next vehicle on the relevant route. Delivery vehicles from different service routes meet at the transfer terminal once every $h_j * h_i/(g_{ji} * y)$ minutes. In Ting's model, link travel time and headways are supposed to be rounded to the nearest integer ratio of the selected base cycle y (*11*).

Different Settings of Time Value Functions

Initially, a constant unit time value of cargo (Figure 3*a*) was assumed. For perishable cargo, the applicable time value functions may be nonlinear, as suggested in Figures 3*b*, 3*c*, and 3*d*.

Figures 3*c* and 3*d* represent a continuous nonconvex piecewise linear function and a nonlinear probabilistic time value function, respectively. A multicommodity network problem can be formulated with multiple values of time (Figure 3*e*) for heterogeneous goods. μ_1 and μ_2 represent different values of time for different cargo.

Solution Approach

Given the proposed nonlinear programming models (e.g., some components of the objective function, constraints, and nonlinear time value settings), sequential quadratic programming (SQP) and a genetic algorithm (GA) were chosen. These methods are well suited for problems with complex and nonlinear formulations (*17*). The SQP method is based on solving a series of subproblems designed to minimize a quadratic model of the objective subject to a linearization of the constraints. If the problem is unconstrained, then the method reduces to Newton's method for finding a point at which the gradient of the objective vanishes. If the model had some nonlinear constraints, Lagrangian relaxation techniques could help maintain the linearization of the constraints (*18–20*). Moreover, GAs are widely used for many optimization problems.

With a GA, a population of candidate solutions to an optimization problem evolves toward better solutions. The evolution usually starts from a population of randomly generated individuals and occurs over generations. In each generation, the fitness of every individual in the population is evaluated. Multiple promising individuals

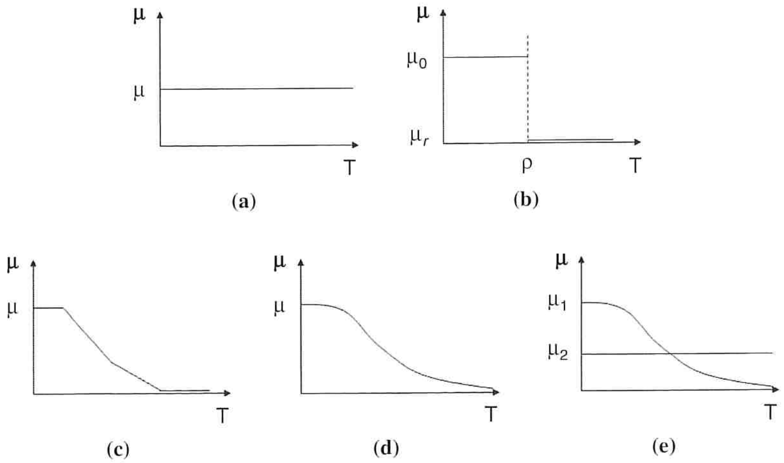
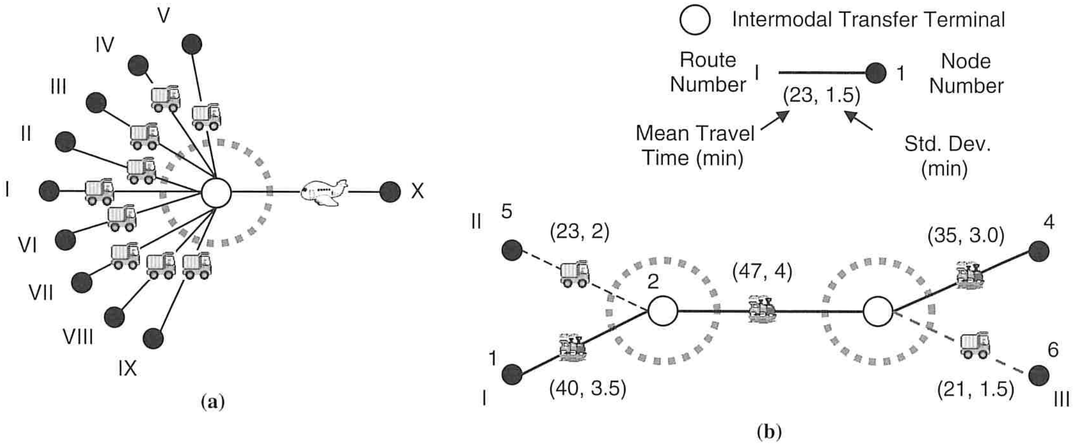


FIGURE 3 Time value functions for perishable cargo: (*a*) single constant, (*b*) threshold, (*c*) continuous nonconvex piecewise linear function, (*d*) nonlinear probabilistic function, and (*e*) multiple time value functions.



(a)

(b)

FIGURE 4 Network configurations for (*a*) Case 1 and (*b*) Case 2.

(also called parents) are stochastically selected from the current population and mutated to form a new population. The new population is then used in the next iteration of the algorithm. In general, the algorithm terminates when reaching the maximum number of generations or a predetermined threshold. A traditional GA can rapidly locate good solutions, even for difficult search spaces. However, it may generate many infeasible solutions and have a tendency to converge toward local optima or even arbitrary points rather than the global optimum of the problem. Diversity is important in GAs because crossing over a homogeneous population does not easily yield new solutions.

In the GA applications, the common service frequency model can be viewed as a special case of the proposed integer–ratio model in which all integer multipliers are equal. More details on model applications and analytical results are provided in the following sections. Demand levels and other factors are set to compare the performances between two cases with different network configurations, as shown in Figures 4*a* and 4*b*.

MODEL APPLICATIONS AND ANALYTICAL RESULTS

This work seeks to coordinate the service frequency among inbound and outbound routes connecting to an intermodal freight terminal. Some applications arise when the service routes have significantly different demand or travel time. In addition, this study provides flexibility for general and perishable cargo with different inventory and dwell time value functions. Intuitively, there may be a significant interaction between different demand levels and schedule coordination operations. If demand decreases, service frequencies should also decrease, thereby increasing the potential value of arrival coordination that reduces missed-connection costs.

Case 1. Single Commodity, Multimode, Single-Hub Operations

In Case 1, there are nine truck routes (Routes 1–9) and one air route (Route 10) connecting to the terminal. To simplify the problem, start from the single hub operation with symmetric demand between any pair of inbound and outbound routes. The capacities for trucks and airplanes are 7,300 and 66,000 lb, respectively. The average vehicle operating costs are \$234/truck hour and \$2,160/aircraft hour. Variable vehicle operating cost (b_i) is \$0.03/lb hour, and the unit cargo dwell cost (μ) is \$0.2/lb hour (*21, 22*). Unit cargo loading and processing time are set as 0.03 and 0.05 min/lb, respectively. Other given inputs are listed in Table 1.

In this case, the common headway coordination method has the same results as the integer–ratio approach. As shown in Table 2, both SQP and GA can obtain better system performances in coordinated operations than in uncoordinated ones, especially for the transfer cost terms. When comparing the optimized results, it is clear that higher service frequencies lead to higher operating cost; lower cargo dwell, loading, unloading, and processing time; and lower cost due to lower load factors. A similar trend is observed in Case 2. There is no intercycle cost when running the common headway coordinated operations.

In this multivariable problem, SQP can generate robust solutions based on given initial feasible solutions. However, the quality of the optimized solutions may be affected by different initial solutions. In the GA applications, the optimized result is almost the same (i.e., the difference between total system costs is only 0.0061%.) The GA-optimized integer–ratio results are illustrated in Figure 5. Although

TABLE 1 Demand and Route Information for Case 1

Inbound Route	Outbound Route (lb/h)	Route Travel Time (min)	
		Mean	SD
1	6,125	82	8
2	7,875	99	9.5
3	3,875	43	3.5
4	8,125	107	10
5	3,750	39	3.5
6	5,625	79	7.5
7	8,750	115	10.5
8	7,500	94	9
9	5,250	73	6.5

NOTE: SD = standard deviation.

TABLE 2 Overall Results of Different Policies in Case 1

	Uncoordinated		Coordinated (GA)		Coordinated (SQP)	
	Optimized Headways (h)	Frequencies (veh/h)	Optimized Headways (h)	Frequencies (veh/h)	Optimized Headways (h)	Frequencies (veh/h)
Route						
1	0.7012	1.4261	0.8343	1.1986	0.8343	1.1986
2	0.6809	1.4686	0.8343	1.1986	0.8343	1.1986
3	0.6375	1.5686	0.8343	1.1986	0.8343	1.1986
4	0.6966	1.4355	0.8343	1.1986	0.8343	1.1986
5	0.6175	1.6194	0.8343	1.1986	0.8343	1.1986
6	0.7175	1.3937	0.8343	1.1986	0.8343	1.1986
7	0.6962	1.4364	0.8343	1.1986	0.8343	1.1986
8	0.6797	1.4712	0.8343	1.1986	0.8343	1.1986
9	0.7137	1.4011	0.8343	1.1986	0.8343	1.1986
10	0.9301	1.0752	0.8343	1.1986	0.8343	1.1986
Slack Time (min)						
s_1^1	—		0.0089		0.0085	
s_2^1	—		0.0028		0	
s_3^1	—		0.0039		0.0037	
s_4^1	—		0.0119		0.0117	
s_5^1	—		0.0104		0.0107	
s_6^1	—		0.0078		0.0079	
s_7^1	—		0.0126		0.0128	
s_8^1	—		0.0099		0.0099	
s_9^1	—		0.0068		0.0068	
s_{10}^1	—		0		0	
Cost ($/h)						
Operating cost	18,659		18,526		18,526	
Dwell cost	9,341		9,626		9,626	
Loading–unloading	18		19		19	
Cargo processing	15		16		16	
Nontransfer cost	28,033		28,187		28,187	
Intercycle	—		0		0	
Slack time	—		119		114	
Missed connection	—		4,532		4,537	
Connection delay	—		36		34	
Transfer cost	9,341		4,687		4,685	
Total system cost	37,374		32,874		32,872	

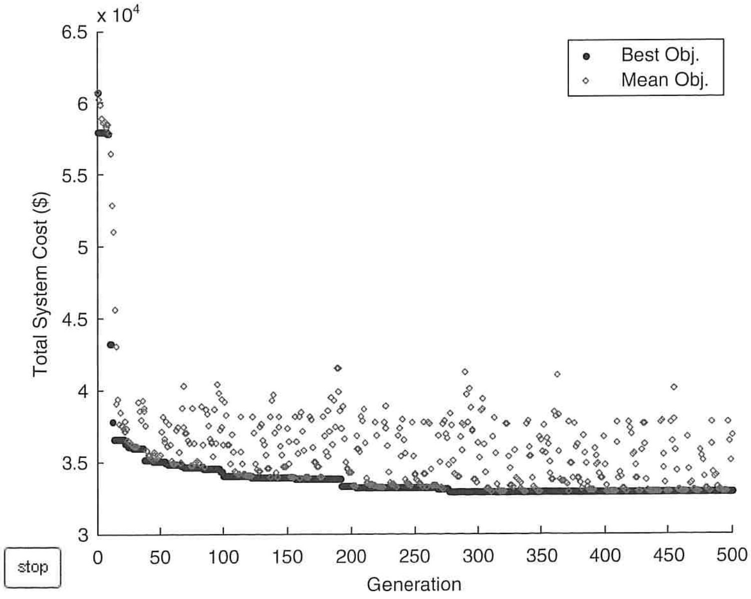


FIGURE 5 Results of genetic algorithm (500 generations) in Case 1.

TABLE 3 O-D Demand Information for Case 2 (lb/h)

O-D (Types 1 and 2)	O-D (Types 1 and 2) 1	2	3	4	5	6
1	0 0	1,650 1,650	1,450 1,450	1,700 1,700	1,450 1,450	465 465
2	1,650 1,650	0 0	3,185 3,185	1,450 1,450	1,060 1,060	1,650 1,650
3	1,450 1,450	3,185 3,185	0 0	2,125 2,125	1,700 1,700	1,910 1,910
4	1,700 1,700	1,450 1,450	2,125 2,125	0 0	635 635	1,760 1,760
5	1,450 1,450	1,060 1,060	1,700 1,700	635 635	0 0	0 0
6	465 465	1,650 1,650	1,910 1,910	1,760 1,760	0 0	0 0

the GA objective value can be improved by running additional generations, those additional generations yield diminishing improvements. The proper number of generations that should be run depends on tradeoffs between solution quality and the program running time. Behrang et al. have proposed some hybrid GA–SQP optimization techniques that might be used to refine further research (*23*).

Case 2. Multicommodity, Multimode, and Multihub Operations

Two truck routes and one rail route are analyzed in Case 2 (Figure 4*b*). The vehicle capacities for truck and rail are 22,000 and 100,000 lb, respectively. The average vehicle operating costs are \$710/truck hour and \$3,240/rail hour. Two types of shipments with different unit time values are assumed in this case, as suggested in Figure 3*e*. μ_1 and μ_2 are equal to \$0.5 $*$ exp($-t$)/lb-h and \$0.2/lb-h. The notation "t" expresses the total transportation time, including dwell time, loading and unloading, cargo processing, and mean travel time from origin to destination. The demand information is shown in Table 3. All other settings are as in Case 1.

As shown in Table 4, the integer–ratio schedule coordination outperforms the uncoordinated and the common-headway coordinated operations for the given input information. Similarly to Case 1, schedule coordination can reduce transfer costs more than the uncoordinated system. Transfer costs can still be reduced by up to 40.76% in common coordinated operations; however, the common headway method is inefficient, with higher nontransfer costs when the demands or lengths of different routes vary much. s_1^{2a} and s_1^{2b} express slack times of Route 1 at transfer terminal 2 with two service directions. The optimized base cycle of the integer–ratio schedule coordination is equal to 0.8506 (hours per vehicle). The intercycle costs arise from the cargo transfer from Routes 2 and 3 to Route 1. Both SQP and GA can reach similar results; the difference in total system costs is only 0.008%.

CONCLUSIONS

In this paper, an analytical model is developed for coordinating vehicle schedules and cargo transfers at intermodal freight terminals in order to improve system operational efficiency and minimize total system costs. The proposed general models can be applied to different combinations of modes (e.g., trucks to rail trains, trucks to airplanes, rail trains to ships). Preplanning models are developed for optimizing in advance system characteristics such as terminal capacities, vehicle

TABLE 4 Overall Results for Different Policies in Case 2

	Optimized Headway (h)			
			Integer–Ratio Coordination	
	Uncoordinated	Common Headway Coordination	GA	SQP
Base cycle (y)	—	—	0.8529	0.8506
1	1.7685	1.2888	$2y$	$2y$
2	0.6068	1.2888	y	y
3	0.5391	1.2888	y	y
Slack time				
s_1^{2a}, s_1^{2b}	—	0.0008, 0.0005	0.0002, 0	0.0002, 0.0002
s_1^{3a}, s_1^{3b}	—	0.0008, 0.0005	0.0014, 0.0001	0.0005, 0.0002
s_2^2	—	0.0005	0	0.0002
s_3^3	—	0.0119	0.0001	0.0079
Cost (\$/h)				
C_o	9,070.9	10,655	8,781.3	8,802.3
C_w	6,271.9	6,427	6,684.3	6,666.5
C_l	12.4	13	13.3	13.2
C_p	27	23	27.1	27.1
Nontransfer cost (\$/h)	15,382.2	17,118	15,506	15,509.1
C_i	—	—	603.6	600.4
C_s	—	32	5.5	19.9
C_m	—	765	765.5	765.7
C_d	—	353	379.7	363.8
Transfer Cost (\$/h)	1,941.1	1,150	1,754.3	1,749.8
Total system cost (\$/h)	17,323.3	18,268	17,260.3	17,258.9

sizes, routes, schedules, and probabilistic reserve factors built into operating schedules. Through a series of case studies, the model has shown its ability to jointly optimize service frequencies and slack times. The usefulness of the numerical results can be increased by further developing a real-time control model for dealing with routine and major service disruptions.

Case 1 mainly seeks to analyze the coordinated service frequencies that minimize the total system cost and starts by assuming the constant value of time of cargo shipped through a single hub. When comparing the values for coordinated and uncoordinated objective functions, it can be observed that coordinated approaches are better than the uncoordinated system, especially for transfer costs.

In Case 2, a multihub and multicommodity problem with a nonlinear time value function is explored. The integer–ratio scheduling coordination has the best system performance because the common service frequency is inefficient when the route demands or lengths differ significantly. Given the uncertainties regarding demand and traffic congestion, it would be highly unlikely that all trucks scheduled to meet a rail train actually arrive before that train, unless an excessive and wasteful amount of slack is built into the truck schedules. The right amount of slack—based on tradeoffs between wasting truck costs and terminal storage costs versus missing connections and delaying cargo until the next train departure—is just one of the variables optimized in this model.

Because of the complex and nonlinear nature of the problems, both cases are solved by using SQP or a GA. Results optimized with these two approaches differ very slightly (up to 0.008%). It is found that SQP is highly sensitive to initial feasible solutions. A wide variation in results is seen based on different initial solutions. To resolve this variability in SQP results and reduce the GA running time, a hybrid GA–SQP approach will be explored in further research.

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Truck Productivity, Efficiency, Energy Use, and Carbon Dioxide Output

Benchmarking of International Performance

John Woodrooffe, Klaus-Peter Glaeser, and Paul Nordengen

The Joint Transport Research Centre of the Organisation for Economic Co-operation and Development and the International Transport Forum recently conducted a benchmarking study of the safety and productivity of typical highway transport trucks from various countries. This paper focuses on vehicle productivity and efficiency in regard to the movement of freight. Forty vehicles from 10 countries were examined. The vehicles were designed for longer-haul applications and were classified in three separate categories: workhorse vehicles, which are the most common and can travel on most roads; high-capacity vehicles, which may be restricted to a certain class of road; and very high-capacity vehicles, which may be restricted to specific highways or routes. The metrics used in the analysis include maximum cargo mass and volume capacity, optimum cargo density, fuel consumption, and carbon dioxide output as a function of the freight task. The study found that size and weight regulations have a significant effect on the productivity and efficiency of heavy vehicles, including fuel consumption and vehicle emissions per unit of cargo transported. Significant variations were found among the vehicles from participating countries as well as within vehicle classes. It was also apparent that, in general, higher-productivity vehicles are correlated more strongly with increased cargo volume than with increased cargo mass and that larger trucks are better suited to lower-density freight than are workhorse vehicles. The study also found that it is important to consider the freight task when evaluating vehicle fuel consumption and emissions.

Several studies have examined the fuel use and carbon dioxide (CO_2) output of heavy vehicles. Using larger trucks has been shown to be an effective means of improving transport efficiency (*1–4*). The concept of examining vehicle productivity and efficiency as a function of regulation was discussed by the European Automobile Manufacturers Association and European Council for Automotive Research and Development, the Logistics Research Centre, and M. J. Bradley & Associates, although these studies did not evaluate the productivity of individual vehicles (*5–7*).

Heavy vehicles are regionally unique because their design, axle loading, mass, and volume are influenced by weight and dimension regulations (which can differ significantly across nations). This paper provides a summary of the productivity, efficiency, fuel consumption, and emissions output performance benchmarking task conducted by the authors of this paper for the Organisation for Economic Co-operation and Development (OECD) and the International Transport Forum (*8, 9*). The benchmarking study seeks to examine the productivity impacts of changes in the configuration of heavy vehicles as governed by various international weight and dimension requirements. The assessment was undertaken utilizing a set of measures found to be appropriate for assessing comparative performance. This paper describes the benchmarking of 40 vehicle configurations across 10 member countries and provides detail on the methods used and the vehicle performance results. For the most part, the candidate vehicles selected for benchmarking are vehicles currently in operation.

BENCHMARKING CONCEPT

Member countries were invited to submit representative vehicles for evaluation and to provide their technical information. Each vehicle was classified into one of the following three general categories:

- Workhorse vehicle. This is the vehicle most commonly used for long-haul transport. This vehicle is generally at the upper end of the weights and dimensions that are allowed general or widespread access. Workhorse vehicles were defined in this study as having a gross combination mass (GCM) of less than 50 metric tons and a length of less than 22 m. Of the 40 vehicles in the study, 22 were classified as workhorse vehicles.
- Higher-capacity vehicle. This vehicle is typically operated under restricted access conditions that depend on the suitability of the road network. This vehicle will be heavier or longer (or both) than the workhorse vehicle. Higher-capacity vehicles were defined in this study as having a GCM of up to 70 metric tons and a maximum length of 30 m. Thirteen vehicles were classified as higher-capacity vehicles.
- Very high-capacity vehicle. This vehicle typically operates under permit conditions and often in rural or remote areas. It is heavier or longer (or both) than the higher-capacity vehicle. Very high-capacity vehicles were defined in this study as having a GCM of at least 52 metric tons and a length of at least 30 m. Five vehicles were classified as very high-capacity vehicles.

The University of Michigan Transportation Research Institute and Joint Transport Research Centre conducted a survey of participating countries and compiled the vehicle data.

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CANDIDATE VEHICLES

During this study, 39 vehicle configurations from 10 countries were analyzed. A description of each of the vehicles assessed can be found in Table 1. From the vehicles selected by the OECD member countries, four were identified as being European Union international traffic vehicles, meaning that no member can prohibit the use of these vehicles in international traffic within its territory. These vehicles have been referred to as European vehicles (Europe 1, Europe 2, Europe 3, and Europe 4) in Table 1. The remaining vehicles are specific as to their country of origin. For the most part, the vehicles are all currently in service or are being considered for use.

PRODUCTIVITY AND EFFICIENCY BENCHMARKING

The following section addresses heavy vehicle productivity and efficiency in a simplified form, allowing a comparative analysis of the diverse candidate vehicles. The initial analysis examines the maximum cargo mass and volume capacity for each vehicle followed by the optimum density for each vehicle. This analysis considers only dry van–type trailers, which represent the largest trailer type used in most regions of the world. Consideration of other trailer types was impractical given the design and scope of this project. However, trailer type has minimal impact on the results of the comparative analysis because vehicle mass is effectively independent of trailer type, and the van trailer body type represents an approximation of available trailer volumetric capacity. If other trailer types had been considered, it is likely that the relative performance of the various vehicles with that trailer type would be similar.

The cargo mass capacity was determined by subtracting the vehicle tare weight from the allowable gross vehicle weight (GVW) as governed by weight and dimension regulations from the country of origin. The cargo volumetric capacity was calculated from the inner dimensions of the freight compartments as reported in the vehicle surveys.

The analysis of productivity by energy use and CO_2 emissions was conducted at constant highway speed of 90 km/h and did not include drive cycles. A single drive cycle cannot be applied uniformly across the international fleet because of topography and operational and speed limit variations. The primary variables influencing energy consumption for large trucks are vehicle mass, aerodynamic drag, and tire rolling resistance. These variables are highly influenced by size and weight regulation, while other components such as the engine and drive line are more universally similar. Therefore, this study examined only the energy consumed to overcome rolling resistance and aerodynamics on a level ground with no wind effects. The other more universally consistent energy losses associated with the drive line, the engine, and auxiliary loads were applied equally to all vehicles using a simple constant of 225 kWh. Combining this constant with the energy required to overcome tire rolling resistance and aerodynamic losses provides an approximation of total vehicle energy use.

Cargo Mass and Volume Performance

Given that the task of a commercial vehicle is to transport freight, normally limited by either mass or volume, the value of the vehicle and the regulatory system that governs it can be assessed by determining the amount of freight that the vehicle can accommodate. To assess volumetric capacity, the inner dimensions of the freight compartment were used. To evaluate mass capacity, the tare weight of the vehicle was subtracted from the allowable gross vehicle mass. The results of the mass and volumetric capacity of the vehicles evaluated are shown in Figures 1 and 2.

From Figure 1, it can be seen that cargo mass varies significantly within each vehicle category. In all cases, the workhorse vehicle has less cargo mass than the other vehicle classes; however, the high-productivity and very high-capacity vehicles have greater variations in cargo mass than the workhorse vehicles. The poorest cargo mass capacity vehicle is found in the high-capacity category rather than the workhorse category, as would be expected. The U.S. five-axle tractor semitrailer was found to have the poorest cargo mass capacity of any of the workhorse vehicles examined. However, the same vehicle was found to have excellent volumetric capacity.

For the workhorse, high-capacity, and very high-capacity vehicles, the cargo volume capacity increases consistently from the workhorse through to the very high-capacity vehicles, as would be expected. The findings in Figures 1 and 2 suggest that most regulatory systems tend to favor volumetric capacity over mass capacity as vehicle size and weight increases. This volumetric bias may be linked to bridge constraints that tend to lengthen vehicles as mass increases.

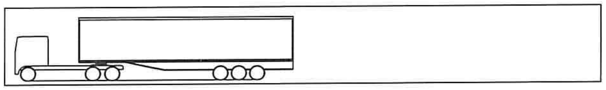
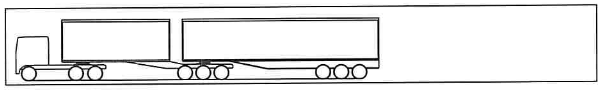
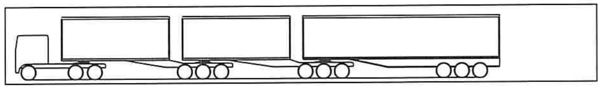
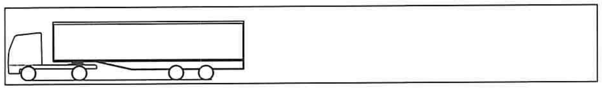
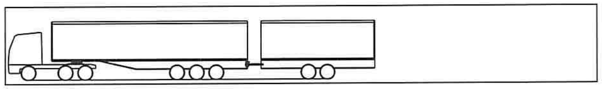
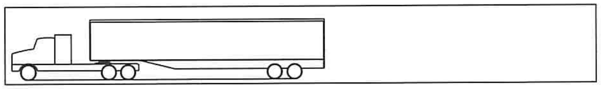
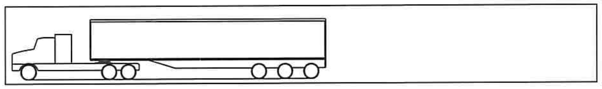
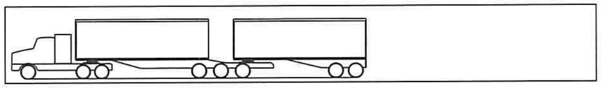
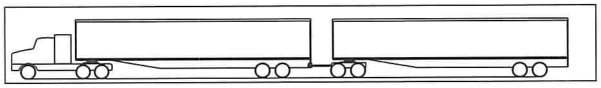
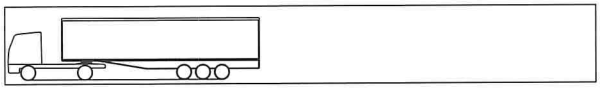
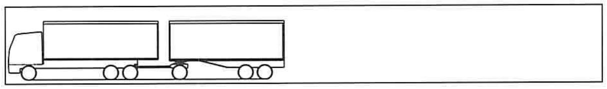
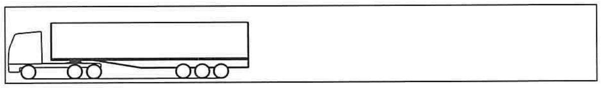
Optimum freight density is defined as the density of freight that would occupy the total available freight compartments of a vehicle while simultaneously reaching the maximum allowable cargo mass of the vehicle. The optimized vehicle density shown in Figure 3 clearly shows that the very high-capacity vehicles are better suited to lower-density freight. In general, workhorse vehicles appear to be better suited to carry higher-density freight, whereas larger vehicles tend to be optimized for lower-density freight. This finding is of particular interest in the rail-versus-truck debate, given that rail is well suited to dense bulk freight. On the basis of the optimum freight density, the results suggest that large trucks and trains generally occupy different ranges of the freight density spectrum.

Payload Efficiency

Payload efficiency is a measure of the proportion of GVW that is utilized for freight transport based on either mass or volume. Observation of Figure 4 shows that payload mass efficiency is a reasonably sensitive measure, showing good variation among all of the vehicles examined. Although variations do occur within each vehicle category, there is little difference among the three vehicle categories; that is, no vehicle category shows significantly superior payload mass efficiency, but vehicles within each category do. This is because of the added tare weight that the high-capacity and very high-capacity vehicles have in relation to the increase in GVW that they are permitted. Given the uniformity among the vehicle classes and the solid variation within the group of vehicles assessed, this measure may be a suitable candidate for productivity performance related to size and weight regulation. The data presented in Figure 4 suggest that payload mass efficiency greater than 0.6 would be desirable for general freight vehicles.

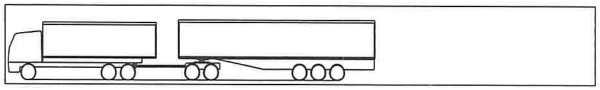
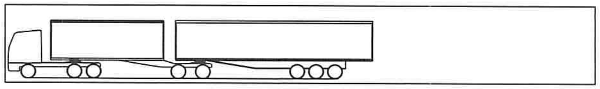
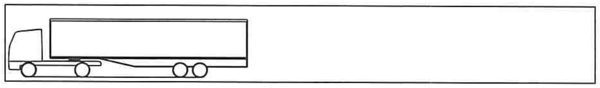
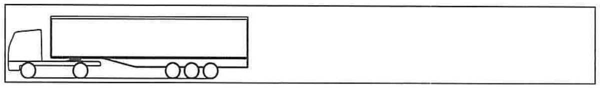
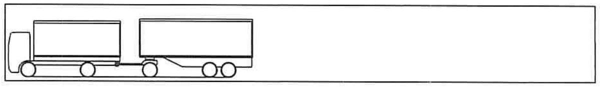
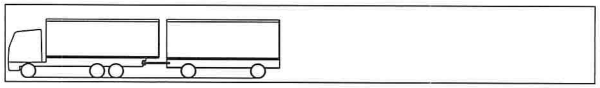
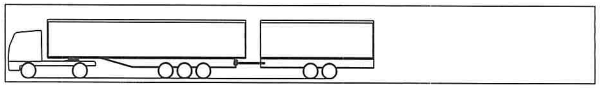
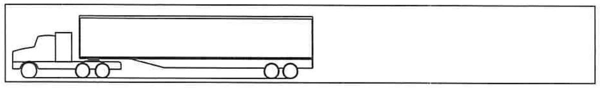
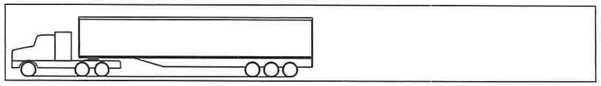
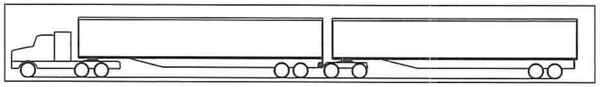
Figure 5 shows that there are large variations in payload volume efficiency within each vehicle class, but that only the very high-capacity vehicles exhibit consistently better payload volume efficiency. This finding is consistent with the earlier observation that higher-productivity vehicles are more likely to have increased volume efficiency than mass efficiency.

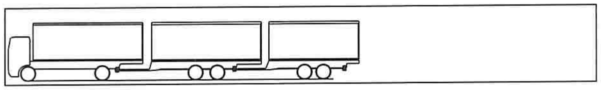
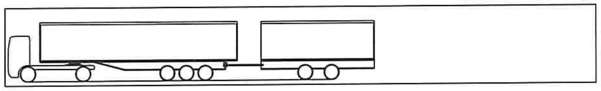
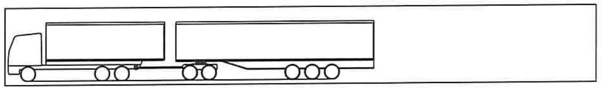
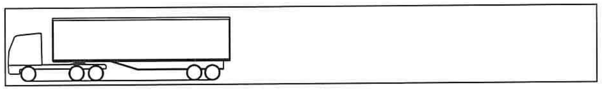
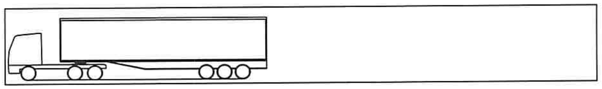
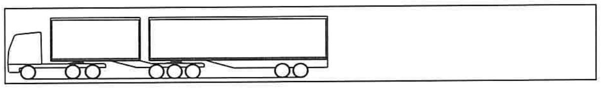
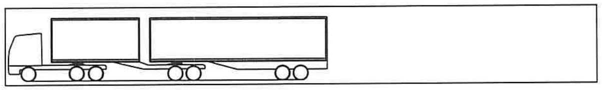
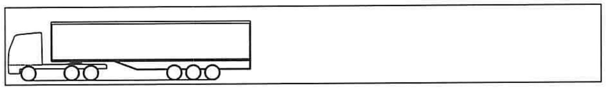
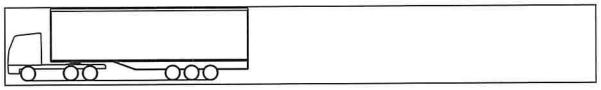
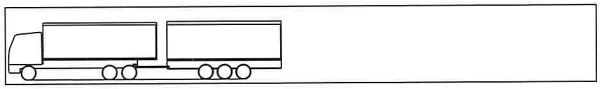
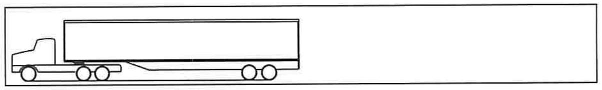
TABLE 1 Vehicles as Analyzed During Benchmarking Study

Vehicle Origin and Identification Number	GCM (t)^a/ Payload (t)^a	Length (m)	Vehicle Classification	Schematic	Vehicle Description and Vehicle Code
Australia 1 AU1-w	45.500 29.000	19.000	Workhorse		Tractor semitrailer T12b3
Australia 2 AU2-h	68.000 44.500	25.010	Higher capacity		B-double T12b3b3
Australia 3 AU3-v	90.500 60.000	33.310	Very high capacity		B-triple T12b3b3b3
Belgium 1 BE1-w	39.000 25.000	16.200	Workhorse		Tractor semitrailer T11b2
Belgium 2 BE2-h	60.000 39.300	25.25	Higher capacity European modular vehicle		Tractor semitrailer with rigid drawbar trailer T12b3a2
Canada 1 CA1-w	39.500 25.300	21.550	Workhorse		Tractor semitrailer T12b2
Canada 2 CA2-w	46.500 31.300	21.550	Workhorse		Tractor semitrailer T12b3
Canada 3 CA3-h	62.500 42.300	20.430	Higher capacity		B-double T12b3b2
Canada 4 CA4-v	62.500 37.300	38.330	Very high capacity		A train double T12b2a2b2
Denmark 1 DK1-w	44.000 30.000	16.480	Workhorse		Tractor semitrailer T11b3
Denmark 2 DK2-w	48.000 32.000	18.750	Workhorse		Rigid truck trailer R12a1b2
Denmark 3 DK3-w	48.000 32.300	16.500	Workhorse		Tractor semitrailer T12b3

(continued on next page)

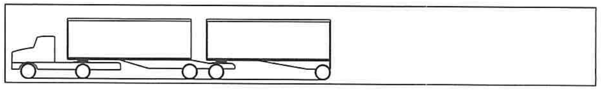
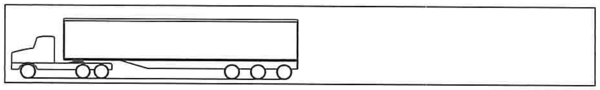
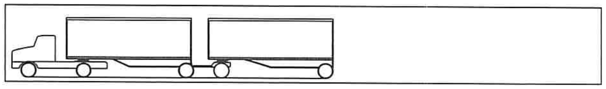
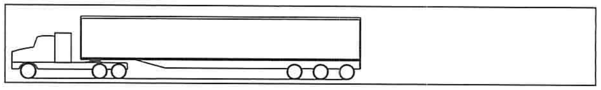
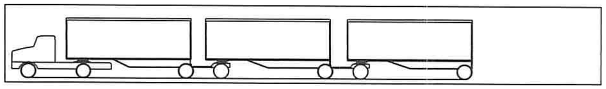
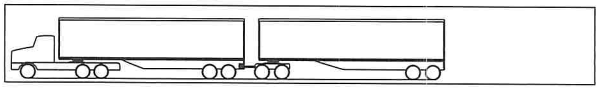
TABLE 1 *(continued)* Vehicles as Analyzed During Benchmarking Study

Vehicle Origin and Identification Number	GCM (t)[a]/ Payload (t)[a]	Length (m)	Vehicle Classification	Schematic	Vehicle Description and Vehicle Code
Denmark 4 DK4-h	60.000 40.700	25.250	Higher capacity European modular vehicle		Truck trailer R12a2b3
Denmark 5 DK5-h	60.000 38.000	25.100	Higher capacity		B-double T12b2b3
Europe 1 EU1-w	38.000 24.000	16.500	Workhorse		Tractor semitrailer T11b2
Europe 2 EU2-w	40.000 26.000	16.480	Workhorse		Tractor semitrailer T11b3
Europe 3 EU3-w	40.000 27.000	16.895	Workhorse		Truck trailer R11a1b2
Europe 4 EU4-w	40.000 21.900	18.750	Workhorse		Rigid truck with rigid drawbar trailer R12a2
Germany 1 DE1-h	40.000 20.800	25.235	Higher capacity European modular vehicle		Tractor semitrailer with rigid drawbar trailer T11b3a2
Mexico 1 MX1-w	44.000 28.649	20.800	Workhorse		Tractor semitrailer T12b2
Mexico 2 MX2-w	48.500 32.349	20.800	Workhorse		Tractor semitrailer T12b3
Mexico 3 MX4-v	66.500 42.849	39.080	Very high capacity		A train double T12b2a2b2

Netherlands 1 NL1-h	50.000 33.410	24.200	Higher capacity		Rigid truck with two rigid drawbar trailers R11a2a2
Netherlands 2 NL2-h	60.000 37.702	25.200	Higher capacity European modular vehicle		Tractor semitrailer with rigid drawbar trailer T11b3a2
Netherlands 3 NL3-h	60.000 39.720	25.240	Higher capacity		Rigid truck trailer R12a2b3
South Africa 1 ZA1-w	43.500 28.140	15.313	Workhorse		Tractor semitrailer T12b2
South Africa 2 ZA2-w	49.300 31.900	17.745	Workhorse		Tractor semitrailer T12b3
South Africa 3 ZA3-h	56.000 33.800	21.972	Higher capacity		B-double T12b3b2
South Africa 4 ZA4-h	56.000 34.240	21.983	Higher capacity		B-double T12b2b2
United Kingdom 1 UK1-w	44.000 29.109	16.500	Workhorse		Tractor semitrailer T12b3
United Kingdom 2 UK2-w	44.000 26.130	16.500	Workhorse		Tractor semitrailer T12b3
United Kingdom 3 UK3-w	44.000 28.000	18.750	Workhorse		Rigid truck with rigid drawbar trailer R12a3
United States 1 US1-w	36.350 (80,138 lbs) 21.150 (46,628 lbs)	19.770	Workhorse		Tractor semitrailer T12b2

(continued on next page)

TABLE 1 *(continued)* **Vehicles as Analyzed During Benchmarking Study**

Vehicle Origin and Identification Number	GCM (t)[a]/ Payload (t)[a]	Length (m)	Vehicle Classification	Schematic	Vehicle Description and Vehicle Code
United States 2 US2-w	36.360 (80,160 lbs) 23.460 (51,720 lbs)	21.980	Workhorse		B-double T11b2b1
United States 3 US3-w	41.900 (92,374 lbs) 26.700 (58,863 lbs)	19.770	Workhorse		Tractor semitrailer T12b3
United States 4 US4-h	36.360 (80,138 lbs) 23.586 (51,998 lbs)	22.060	Higher capacity		A train double T11b1a1b1
United States 5 US5-h	44.100 (97,224 lbs) 28.900 (63,714 lbs)	25.120	Higher capacity		Tractor semitrailer T12b3
United States 6 US6-v	53.752 (118,503 lbs) 37.287 (82,203 lbs)	31.570	Very high capacity		A train triple T11b1a1b1a1b1
United States 7 US7-v	57.040 (125,751 lbs) 32.840 (72,400 lbs)	30.960	Very high capacity		A train double T12b2a2b2

[a] Metric tons.

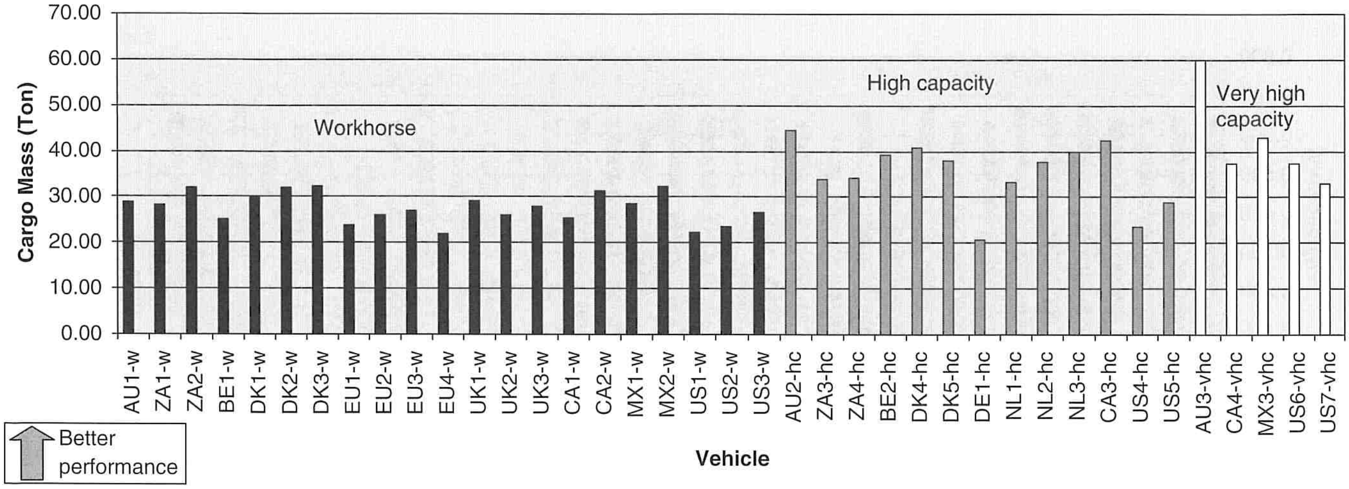


FIGURE 1 Comparison of maximum cargo mass that each vehicle can carry.

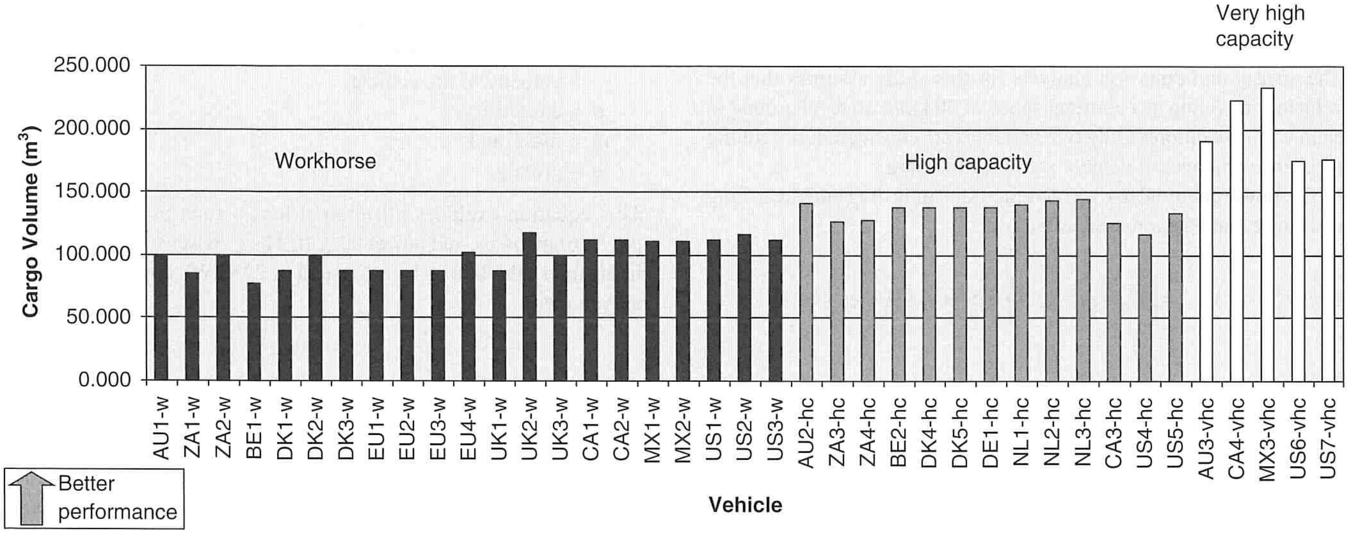


FIGURE 2 Comparison of maximum cargo volume that each vehicle can carry.

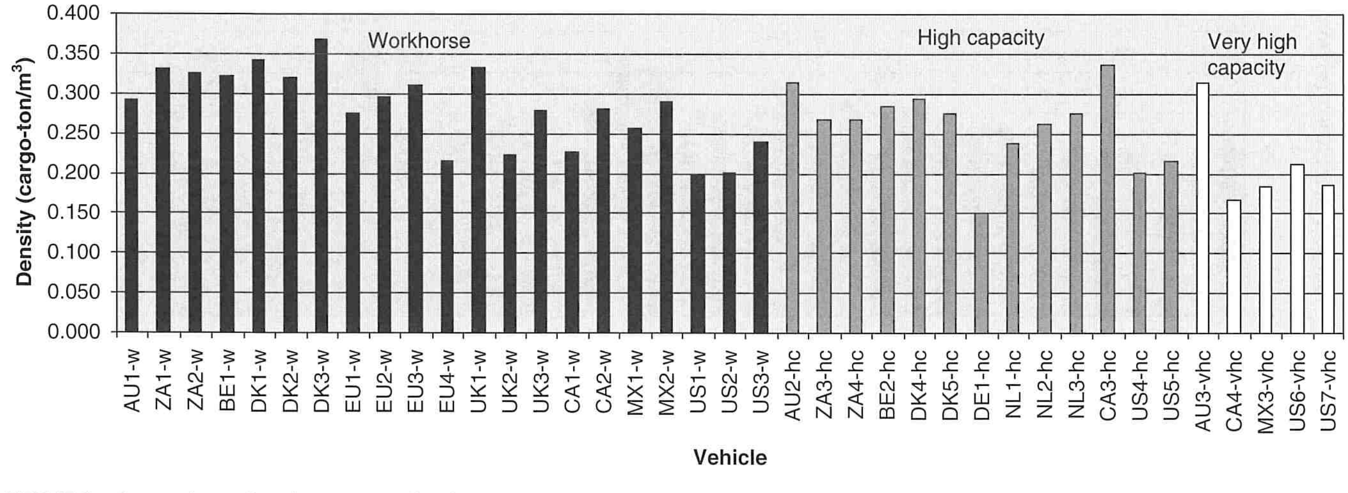


FIGURE 3 Comparison of optimum cargo density that each vehicle can carry.

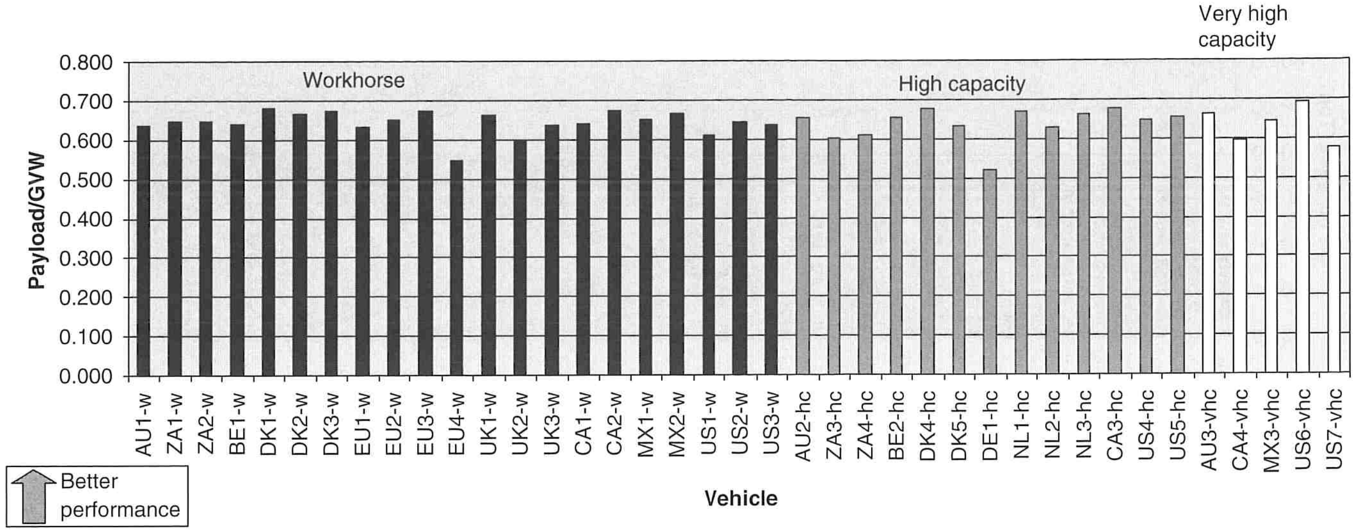


FIGURE 4 Comparison of payload mass efficiency.

Calculating Power, Energy, and CO₂ Emissions

The energy and emission analysis for this study assumes that the vehicle is traveling at a constant speed of 90 km/h on level ground in calm wind conditions. Only two variables are considered: tire rolling resistance and overall vehicle aerodynamic drag.

The power required to overcome aerodynamic drag and tire rolling resistance can be expressed as follows:

$$P=\left(F_R+F_A\right)*v=\left(C_R*m*g+\frac{1}{2}*\rho*C_D*A*v_x^2\right)*v$$

where

P = power required to overcome the resistive forces (expressed as watts),
F_R = tire rolling resistive force,
F_A = aerodynamic resistive force,
C_R = tire rolling resistance coefficient,
C_D = aerodynamic drag coefficient,
A = frontal area of the vehicle,
v = velocity of the vehicle,
ρ = air density,
m = mass, and
g = gravity.

This equation excludes all internal losses such as engine losses, power train losses, and power takeoff. These losses were represented in the final calculations by a constant of 225 kWh applied equally to all vehicles.

Rolling Resistance

A typical C_R value for a traditional dual-tire axle is approximately 0.006 (*1*). Wide-base single tires decrease rolling resistance by up to 20%; therefore, a C_R value of 0.005 was used for wide-base single tires.

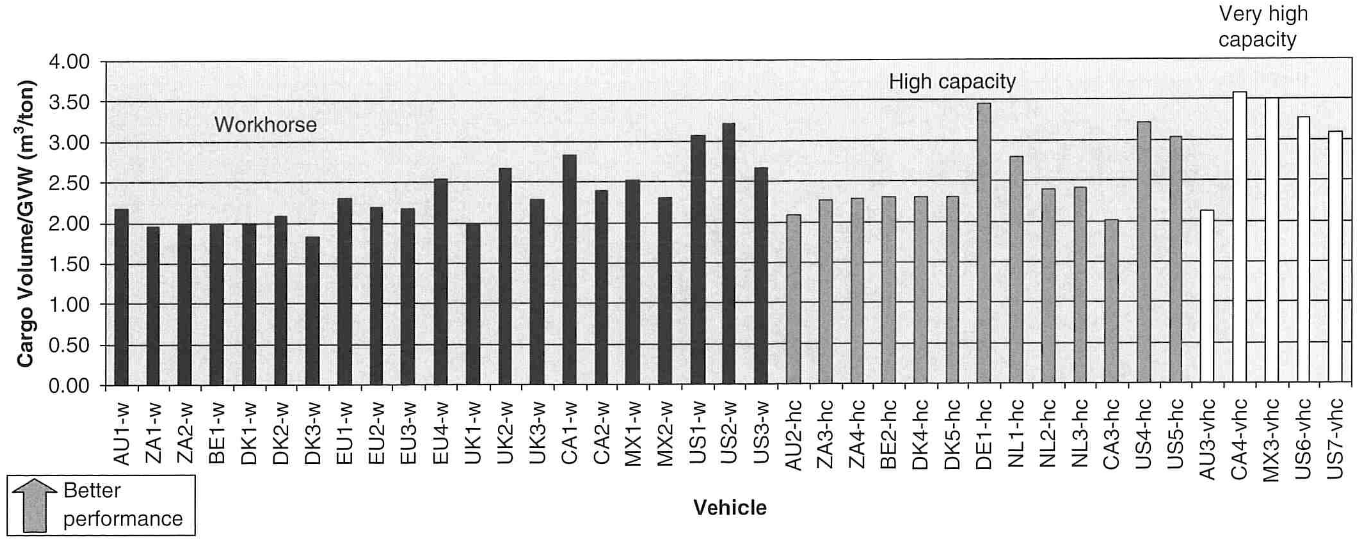


FIGURE 5 Comparison of payload volume efficiency.

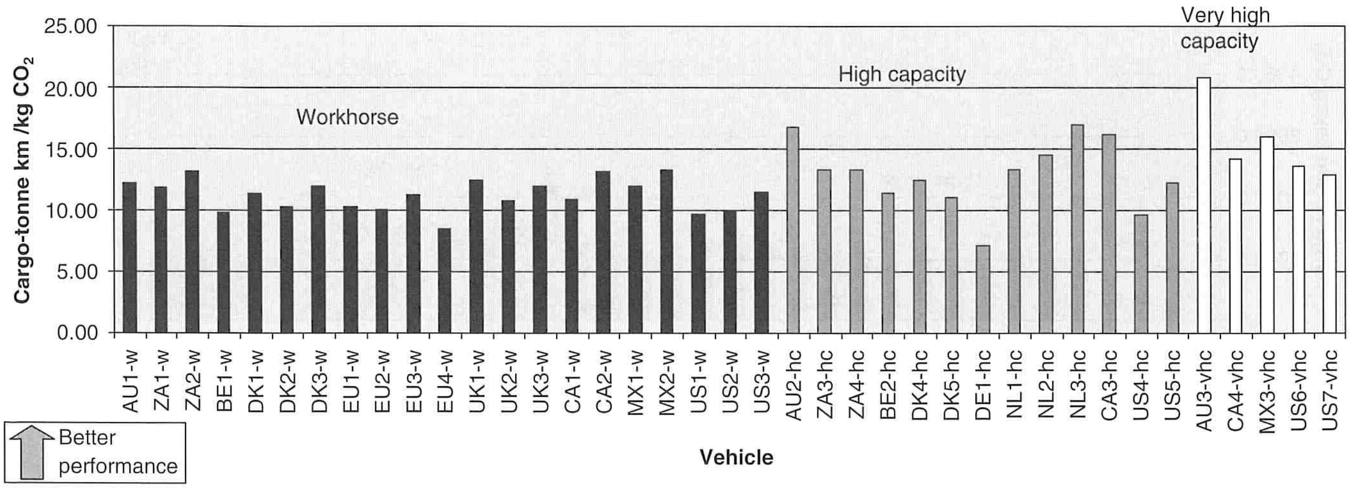


FIGURE 6 Comparison of cargo mass by CO_2 emissions.

Air Resistance

The projected frontal area of a heavy truck varies depending on the design of the truck tractor and the height and width of the trailer. The frontal area for each vehicle was determined from the vehicle data submitted by each member country. The drag coefficient C_D varies depending on the vehicle type and shape. For the purpose of this study, all vehicles were assigned the same drag coefficient (C_D). A value of 0.55 was used, which is typical of tractor–semitrailer combinations. This single value was considered representative for the vehicles assessed in this analysis. For all calculations, air density ρ was assumed to be 1.23 kg/m^3.

The amount of CO_2 produced per kWh is estimated as follows:

- Amount of diesel fuel consumed for truck applications is approximately 200 g/kWh (assuming 50% efficiency).
- Mass of diesel fuel is approximately 850 g/L.
- Amount of CO_2 emissions produced by diesel fuel is 2.668 kg/L.
- Therefore, the amount of CO_2 produced per kilowatt-hour is 0.628 kg (*10*).

Figure 6 shows a comparison of the mass of CO_2 produced in terms of the freight task unit cargo metric ton kilometer. Since fuel consumed is directly proportional to the amount of CO_2 produced, the relative performance of the vehicles in terms of CO_2 produced will be similar to the amount of diesel fuel consumed. In general, heavier vehicles consume more fuel and produce more CO_2. However, vehicles with heavier payloads and lighter tare weight have lower fuel consumption and CO_2 production per cargo metric ton–kilometer; that is, they perform the freight task more efficiently, even though as a vehicle unit, the fuel consumption might be higher. At constant speed, vehicle mass has a relatively small effect on fuel consumption; however, it does become a significant contributor to fuel consumption when vehicles accelerate frequently as part of their duty cycle. For example, the mass of a refuse truck would play a much greater roll in its fuel consumption than that of a long-distance tractor semitrailer because of the frequent stops required along a typical refuse collection route.

The cargo mass volume results shown in Figure 7 are based on the product of cargo mass and volume to account for these two important vehicle attributes. This metric very effectively differentiates the

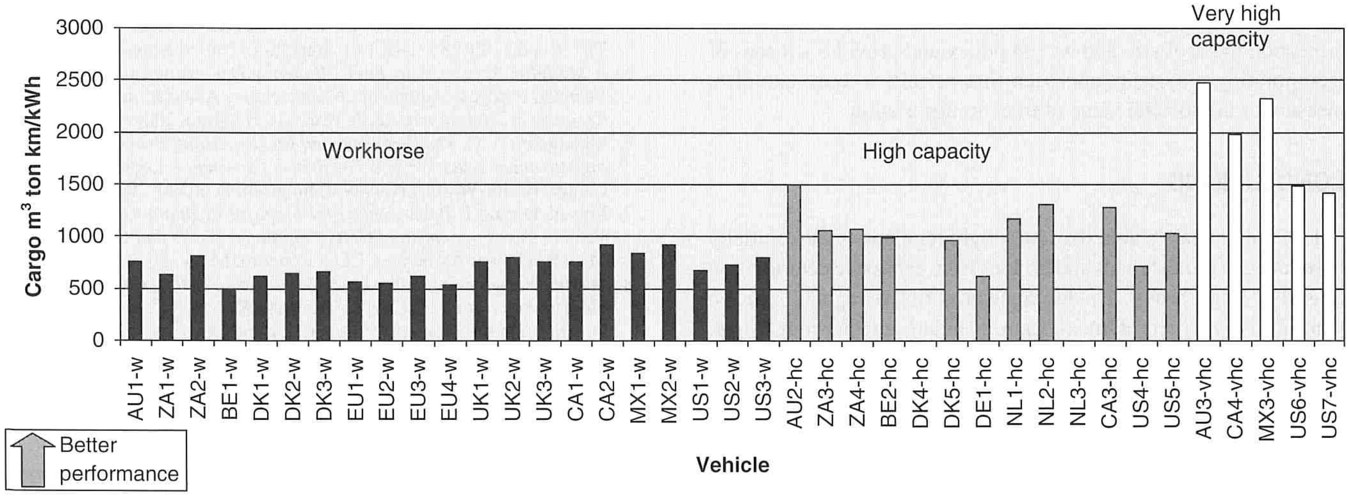


FIGURE 7 Comparison of cargo mass volume by fuel consumption.

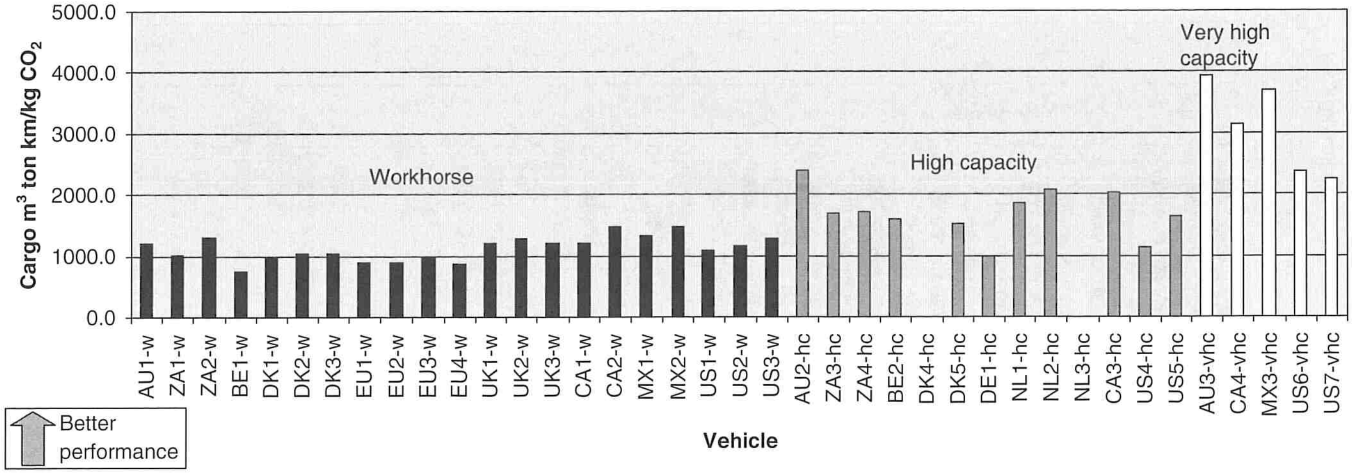


FIGURE 8 Comparison of cargo mass volume by CO_2 produced.

productivity performance of the three vehicle classes. The variations are significant within each vehicle class, and the performance measure results show improvement with each increasing vehicle capacity category. This measure appears to be the most sensitive and revealing of all the productivity measures examined. Because CO_2 production is directly proportional to diesel fuel use, the emissions characteristics relative to each vehicle are the same as those related to fuel consumption, as shown in Figure 8.

IMPLICATION OF FINDINGS

The results of this research clearly demonstrate the influence of truck size and weight policy on vehicle productivity and efficiency. There is significant variation in vehicle performance based on country and vehicle class. The metrics used in the analysis provide a means of not only evaluating vehicle performance but also providing insight into the effectiveness of size and weight policy. Using such metrics during the process of policy development will ensure that vehicle performance and efficiency can be optimized within the context of infrastructure compatibility.

From this research, it is evident that size and weight policy provides a practical avenue for improving vehicle efficiency and reducing fuel consumption and vehicle emissions for a given freight task. This represents a significant departure from the traditional infrastructure protection focus of size and weight policy and provides a means of incorporating a systems approach that permits a more complete measure of the societal value of truck transportation.

CONCLUSIONS

1. Commercial vehicle size and weight regulations were initially introduced to protect roads and bridges from excessive deterioration caused by large, heavy vehicles. Such prescriptive regulations have influenced key aspects of truck design, including length, width, height, wheelbase, number of axles, axle loads, axle spacing, and GCM. These vehicle characteristics influence vehicle productivity, fuel use, and emission output. Therefore, size and weight regulation represents a tool that can not only protect the infrastructure but also create vehicles that provide significant societal benefits.

2. From the vehicles examined in this analysis, it is apparent that higher-productivity vehicles correlate more strongly with increased cargo volume than increased cargo mass. In general, larger trucks are better suited to lower-density freight than workhorse vehicles; however, exceptions do exist.

3. A vehicle having low fuel consumption is not necessarily a vehicle having good fuel or emissions efficiency. Fuel consumption and emissions output relate to fuel used to move a vehicle. Fuel efficiency relates to fuel used to accomplish a specific freight task.

4. For the vehicles examined in this study, using fuel efficiency and CO_2 produced relative to the product of cargo mass and volume was found to be the performance measure most effective at differentiating vehicle efficiency performance.

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The Motor Vehicle Size and Weight Committee peer-reviewed this paper.

Intra-Industry Trade Analysis of U.S. State–Canadian Province Pairs

Implications for the Cost of Border Delay

Kristján Árni Kristjánsson, Michael Bomba, and Anne V. Goodchild

Intra-industry trade (IIT) occurs when trading partners import and export similar products. A high volume of IIT of horizontally differentiated goods implies a deep level of regional integration, stable regional trading patterns, and potentially significant consequences from border delay. In this paper, trade between Washington State and British Columbia, Canada (the Cascade gateway), is compared with trade between Michigan State and Ontario, Canada (the Great Lakes gateway). The Grubel–Lloyd index, which measures IIT, is used to analyze trade in these two corridors. Higher levels of IIT and regional integration within the Great Lakes gateway are shown. The paper argues that cross-border supply chains most exposed to higher cost from increasing border delays are composed of horizontally differentiated manufactured goods having high levels of IIT and relying heavily on truck transportation. These types of goods are more common in the Great Lakes gateway, and this region may therefore experience greater economic impacts from long and unpredictable delays than the Cascade gateway.

The value of trade between the United States and Canada is the highest of that between any two countries worldwide, and Canada is the largest foreign trading partner for 37 of the 50 U.S. states (*1*, *2*). The border between the countries is 5,525 mi, making it the longest common border in the world, with 12 U.S. states bordering seven Canadian provinces (*3*). The commodities traded in different parts of this border are varied, and so is the nature of that trade. Most of this trade—almost 63% of the total value and 35% of the weight—is moved by trucks, which are often subject to long and unpredictable delays at the border crossings (*4*). This paper uses the Grubel–Lloyd (GL) index, a measure of intra-industry trade (IIT), to describe the nature of the trade along the U.S.–Canada border and its relation to trade corridors. It is argued that increasing delay for roadway vehicles crossing the borders has different impacts on intra-industry versus interindustry trade and that knowledge of these impacts should be considered in evaluating potential policy solutions to addressing border congestion.

BACKGROUND

Intra-Industry Trade

International trade has historically been studied as occurring between countries importing or exporting commodities based upon comparative advantage. The two primary theories for studying nation-to-nation trade are the Ricardian and Heckscher–Ohlin approaches, both of which assume that trade occurs between countries based on their comparative advantage or factor endowments (*5*). This type of trade is called interindustry trade, and it involves a country exporting goods that it is most suited to produce while importing goods that it is least suited to produce. However, more than half of global trade today is IIT: the trade of goods or services that occurs between trading partners within the same industry. The "new trade theory" considers economies of scale and product differentiation rather than production under conditions of perfect competition. IIT has been the fastest-growing component of global trade flows since World War II (*6*). IIT has gone up for all types of goods and services, including oil and natural gas, manufacturing parts, foods and beverages, and services (*7*). Falling transportation costs and increased productivity, technology, improved skill levels, and reduced tariffs through trade agreements (as in the case of North America) have allowed countries to trade similar products.

U.S.–Canada Trade

Between 1994 and 2000, the value of trade between the United States and Canada grew on average 7.2% annually. This growth was for the most part the result of the implementation of the North American Free Trade Agreement (NAFTA) in 1994 (and the Free Trade Agreement between the United States and Canada before that in 1988), which removed many barriers to trade and investment among the United States, Canada, and Mexico (*8*). The ratification of the General Agreement on Tariffs and Trade, signed by the United States and Canada in 1948, also had a significant impact on North American trade and played a major role in the expansion of world trade in the second half of the 20th century (*9*). In the last two decades of the 20th century, trade within the countries of North America grew dramatically. This trade increasingly consisted of cross-border supply chains linking production, distribution, and the consumer market across the countries (*10*).

The terrorist attacks of September 11, 2001, resulted in increased emphasis on security at borders, with many changes in security processes mandated by legislature. The changes included the Advanced

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Electronic Presentation of Cargo Information program under the U.S. Trade Act, the Customs-Trade Partnership Against Terrorism, the Free and Secure Trade program, and the U.S. Food and Drug Administration's (FDA's) prior notice arrival policy (*11*).

Along the U.S.–Canada border, there are at least three geographically distinct land corridors or "gateways" where unique regional conditions exist. In the Pacific Northwest, the Cascade gateway between western Washington and the lower mainland of British Columbia (BC) includes the fourth-busiest commercial crossing on the northern border, located at Blaine between Washington and BC. The Great Lakes gateway is the busiest section of the border, with major crossings at Detroit and Port Huron between Michigan and Ontario, as well as crossings at the Buffalo and Niagara peninsula between New York and Ontario (*3*). Trading volumes are significantly larger in the Great Lakes gateway, and border research has typically focused on trade in this region. Less attention has been given to the western portion of the northern border, even though the port of entry at Blaine is the fourth-busiest crossing on the northern border. A recent paper by Goodchild et al. does describe commercial cross-border trips in the Cascade gateway and trade corridor (*11*). This work demonstrates that the commodity profile is quite different than that of the Great Lakes gateway. At the Cascade gateway, wood, paper, and plastics are the dominant commodities, the movement of which is not viewed as particularly time critical. Within the Great Lakes gateway, the situation is significantly different, and manufactured goods flow across the border in a time-sensitive environment (*11*).

IIT's Relation to Transportation Corridors and Border Delay

Many have argued that NAFTA has achieved greater economic integration between the United States and Canada. Integration exists when product flow between countries occurs on the same terms and conditions as product flow within countries (*12*). High volumes of trade alone do not necessarily demonstrate good economic integration between countries. Growing levels of IIT are a better measure of integration and demonstrate that countries frequently trade within industries in which they both have a high degree of specialization. High levels of IIT may also lead to stable trade and transportation corridors, as corridor development is more likely to be based on intra-firm relationships. Firms take advantage of specialization, labor costs, labor productivity, and transportation costs by splitting tasks. This type of collaboration is common in the automotive industry in Michigan and Ontario, where many companies have operations on both sides of the border (*2*). This integration in the automotive industry was the result of the Canada–United States Automotive Agreement, commonly referred to as the Auto Pact, signed in 1965. The agreement eliminated trade tariffs on cars, trucks, buses, tires, and automotive parts between the two countries and created a single North American manufacturing landscape. Parts may travel back and forth across these borders not as finished products, but as intermediate goods during the manufacturing process. A vehicle manufactured in North America crosses the border, on average, seven times during its assembly, as the power train is attached to the body, seats are installed, and brakes, lights, and other elements are added (*3*). Border delays are therefore not experienced just once during the production of a vehicle, but many times. Figure 1 shows a simplified schematic of a supply chain. The arrows indicate transportation, and the boxes indicate fixed locations. The last box is the consumer, and the circles indicate possible locations for delay. Freight transportation is performed in the service of trade. If border delays are experienced in the service of IIT, it is more likely to occur higher up the supply chain, as goods are not yet ready to be delivered to customers. In the case of interindustry trade, it is more likely to be the transportation of finished goods being moved to the customer (be that a consumer or another enterprise). Given this, delay within an IIT supply chain also has the ability to affect subsequent transport links.

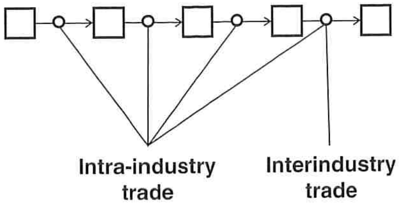


FIGURE 1 Possible locations for delays in supply chain for intra-industry and interindustry trade.

Supply chains vary in structure and are affected differently by border delays. In the automotive industry, goods could be crossing the border while moving from factory to factory, while other kinds of goods could be crossing the border as they head to a warehouse for storage. Delays will not affect the latter type of goods in the same way they affect the former type, because they do not put a stop to manufacturing. Supply chains using just-in-time methods and those relying on the transportation system to ship intermediate goods repeatedly between factories during manufacturing will experience larger costs from border delay than those keeping large inventories. Delayed shipments may result in factory shut-downs and may affect multiple subsequent activities downstream.

Horizontal IIT (HIIT) refers to the IIT of horizontally differentiated products (i.e., similar products), and vertical IIT (VIIT) refers to the IIT of vertically differentiated products (i.e., products differing by quality or consumer preference). HIIT involves intra-firm relationships moving equal-quality intermediate goods from factory to factory during manufacturing. In VIIT, two-way trade of products within the same category is occurring, but the commodities differ in quality and price. This type of trade is generally not based on strong relationships, and if the cost of crossing the borders increases, the prices of the goods increase, and the corridors may cease to exist or shift to another location. This shift could be a shift in point of entry or mode, or it could involve the substitution of goods. Recall that IIT involves the trade of goods that the importer and exporter both have; thus, an importing country may easily choose to acquire goods and commodities from another exporting country that offers a lower price or higher quality. Fontagné et al. suggest using unit prices to divide IIT into HIIT and VIIT. If the prices are similar (where 15% or 25% thresholds are often used), the IIT is horizontally differentiated (*13*).

Where high volumes of trade exist but low levels of IIT are observed, trade is generally based on factor endowments and comparative advantage; thus, the goods being imported are those that the importing country does not have or does not produce enough of. Although other sources may be found for the commodities, they may always be more expensive to acquire. The main east and west trade corridors will be analyzed here with respect to these three trade patterns: HIIT, VIIT, and interindustry trade.

Cost of Delay

Delays for vehicles crossing the border have direct and indirect cost implications for to the carrier and manufacturer of the goods. Quantifying these costs is difficult, and this study does not attempt to do so. A study by the Conference Board of Canada in 2007 identified how border delays affect various industries. According to the study, food-exporting companies may bear the highest cost. These companies need to notify border officials 2 h in advance of impending shipments, while 1 h is required for nonagricultural shipments. These shipments also need to be made during daytime hours, since FDA inspectors work only during the day. Exporters of agricultural products also need to go through interviews or inspections with multiple agencies with few links between them, including U.S. Customs, the U.S. Department of Agriculture, and the FDA (*14*). The Conference Board report further identified seven sectors considered most vulnerable to increased border delays. The report states that small increases in costs could shift important future location decisions, because these industries have a large share of trade and are dependent on truck transportation. These industries [at the North American Industry Classification System (NAICS) 4-digit level] are

1. Motor vehicle manufacturing;
2. Basic chemical manufacturing;
3. Computer and peripheral equipment manufacturing;
4. Resin, synthetic rubber, and artificial and synthetic fiber manufacturing;
5. Rubber product manufacturing;
6. Seafood product preparation and packaging; and
7. Electrical equipment and component manufacturing.

These are primarily manufacturing industries. Excluded in this analysis are activities that are linked to raw materials extraction (*14*).

Unexpected delays force assembly lines to slow down and even stop when parts do not arrive as scheduled. Delivery of parts must be coordinated within hours or even minutes of when they are needed in a just-in-time business environment such as the automotive industry (*3*). An automotive case study prepared for the Canadian Department of Foreign Affairs and International Trade in January 2002 concluded the following:

1. The industry's standard practice to manage a border crossing was a window of 20–30 min;
2. Delays above 60 min typically result in an assembly plant disruption, forcing companies to increase inventory;
3. Every additional hour of inventory costs $432,000 to cover the risk of shipment disruptions of Canadian parts to U.S. plants; and
4. For U.S. parts flowing into Canada, the impact of delays equated to $800,000/h of inventory charges (*15*).

With interindustry trade, this amplification of border delays down the supply chain is not seen, because delays generally occur downstream at a single location in the supply chain.

Previous Research

Previous research on U.S.–Canada IIT patterns has primarily involved economic studies at the national level rather than an examination of at IIT at the regional level or in the context of transportation corridors. Recent research includes a study conducted by Brülhart and Thorpe that revealed steadily growing IIT levels from 1990 to 1998, particularly in manufacturing goods (*16*). Fontagné et al. concluded that the United States and Canada have the largest flow of bilateral IIT worldwide, although the countries having the highest share of IIT in their trade are Germany and France (*17*), and a study by Vogiatzoglou and Patras showed that comparative advantage is losing importance in driving trade and specialization patterns within NAFTA (*18*).

Bomba proposed using IIT trade analysis to better understand North American trade and transportation corridors. His proposal underlies this research, which seeks to provide a better understanding of the nature of regional trade between the United States and Canada. This study will show that trade between Michigan and Ontario is highly integrated with high levels of IIT of horizontally differentiated goods, whereas trade between Washington and BC is mainly interindustry trade or IIT of vertically differentiated goods. This trade pattern has implications for the economic consequences of delay and the nature of transportation in the two regions.

METHODOLOGY

GL Index

One of the first measures of IIT was developed by Balassa, who used the measure to determine whether the European Economic Community was creating an interindustry or an IIT specialization (*19*). Several economists have since derived new methods to measure IIT. Unsatisfied with Balassa's method, Grubel and Lloyd altered the equation into what has become the most commonly used measure of IIT. Their method measures IIT as a percentage of a country's total trade (exports plus imports), where the value of exports of an industry is exactly matched or balanced by the value of imports from the same industry. Any remaining trade is the IIT. For an individual industry *i*, the formula is

$$B_i = \frac{\left[(X_i + M_i) - |X_i - M_i|\right]}{(X_i + M_i)} \times 100 \tag{1}$$

where X_i and M_i stand for the exports and imports of a commodity or industry *i*, and B_i is the value of IIT as a percentage of total trade (*20*). The resulting value of B_i is between 0 and 100. A value of 100 would mean that an equal amount of trade is being imported and exported within an industry, and a value of zero means that there is no reciprocal trade to imports or exports within that industry.

Grubel and Lloyd also derived a summary formula, a method to obtain the average level of IIT for trading partners by calculating the weighted mean, using the relative size of exports and imports of a particular industry:

$$B_j = \frac{\sum_{i=1}^{n}(X_i + M_i) - \sum_{i=1}^{n}|X_i - M_i|}{\sum_{i=1}^{n}(X_i + M_i)} \times 100 \tag{2}$$

The advantage of the summary formula is that it uses the weighted mean of industries rather than just calculating the average of all B_i values, which would result in a misleading average because the importance of some products is greater than others (*20*). A downside to the GL index is that when comparing each individual industry IIT level by calculating the B_i values, the index is relative to the total trade within that industry; thus, it does not include factors that account for the amount of trade or the importance of that industry.

Connecting Trade to Trips

A variety of modes are used to carry out the transportation required in support of the trade presented in the intra-industry analysis. Road and rail are the predominant modes. The interest here is in the trade moved by truck and therefore affected by commercial vehicle border delays. The analysis identifies which industries may be excluded from an analysis of the impacts of commercial vehicle border delays caused by heavy reliance on other modes than truck, as well as which industries rely on the truck transportation system more than others. Data from the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS) provide some insight into how often each commodity is moved by each mode. These data provide a rough idea of the mode share (as opposed to the exact mode share) of the trade presented in the IIT analysis, as BTS uses commodity codes from the Harmonized Tariff System, which are different than NAICS codes. The numbers for mode share are retrieved from a 2008 summary of trade crossings between the state–province pairs.

DATA

Annual trade between the United States and Canada (in U.S. dollars) by state–province pairs is used to calculate the GL index. Data are obtained from Industry Canada. These trade data are categorized using the NAICS. The data cover the years from 1992 to 2008. These data enable analysis of the total IIT level between different states and provinces in the United States and Canada. The full six-digit code provides very detailed industry classification but may present truly related industries as separate. For example, there are 13 different code classifications at the six-digit level for automobile and automobile parts manufacturing. Using only the first three digits aggregates all activities for airplane manufacturing and automobile manufacturing into the same industry. Using a smaller number of digits will increase the value of the GL index, because more economic activity is assigned to the same industry classification. The four-digit code will mainly be used here, which strikes a balance between aggregating diverse industries and separating related industries into categories used for analysis. The three-digit code will also be used in the IIT analysis for comparison. A limitation of data disaggregation is that an intermediate good may eventually be classified differently, such as automobile parts that are assembled into a vehicle and may finally be crossing the border as a finished product. This affects the GL index calculations because the same product is categorized in two industry codes. Therefore, calculations for both the three- and four-digit NAICS codes will be shown in the IIT analysis.

Data on goods moving into Canada are collected by the province or state of clearance, which will coincide with the location of border crossing unless the goods are moved in bond to their destination. Goods moving to the United States are collected by province or state of origin and data indicate where the goods were grown, extracted, or manufactured. This may not always coincide with the province where the goods were cleared by Customs, but given Canada's linear geography and more limited transportation infrastructure, if goods originate in BC and are destined for the United States, it is reasonable to assume that they crossed the border at this location (*21*). The value of trade is presented in current U.S. dollars (unadjusted for inflation).

Trade data are also available from the BTS website, along with a variety of other useful data. BTS data are classified by two-digit Harmonized Tariff System codes, which do not match the NAICS codes. Data on U.S. imports are compiled from data collected by the U.S. Customs and Border Protection's Automated Commercial System, import entry summary forms, warehouse withdrawal forms, and Foreign Trade Zone Documents. U.S. export data are compiled from the Automated Exports System, paper Shipper's Export Declarations, and Canadian data provided by Statistics Canada (*22*). These trade data are available by value and weight, and the user is able to retrieve data by port and mode. Using BTS data for GL index calculations results in very high indices, which indicates that these data are highly aggregated and will not be used for that purpose. Data on the number of trucks crossing at each border station at the U.S.–Canadian border are also retrieved from BTS. These data are available only for trucks entering the United States.

The top 10 industries in terms of value of trade are analyzed for province–state pairs, using average values of the 8-year period from 2001 to 2008. The average value over the year was used to smooth out seasonal variability.

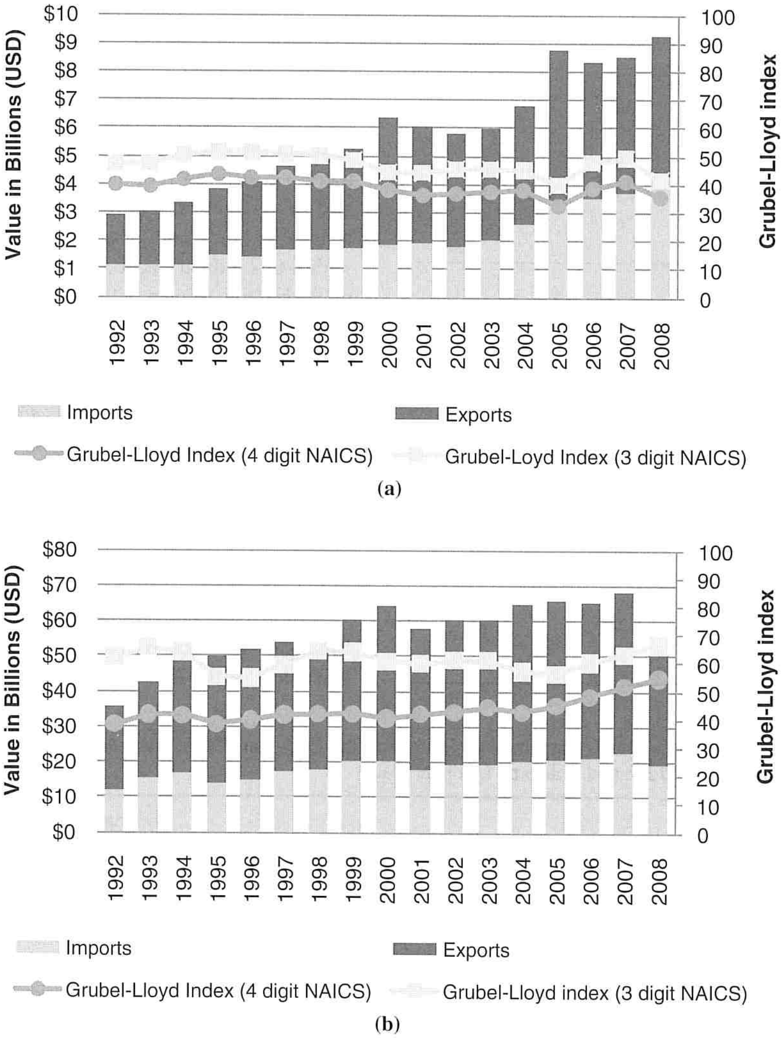
DATA ANALYSIS

Comparison of Key East–West Corridor Trade

The summary of GL indices between Washington and BC and between Michigan and Ontario is shown in Figure 2. The values are shown for each year from 1992 to 2008, along with annual imports and exports. The index is shown for both three- and four-digit NAICS codes. The GL indices between Washington and BC are fairly consistent in the period, hovering around 40 at the four-digit level and around 45 to 50 at the three-digit level. The fact that the difference between the GL indices at the three- and four-digit levels is consistent throughout the period indicates a stable commodity profile, because the three-digit codes cover different numbers of 4-digit codes. Between Michigan and Ontario, the index has risen from approximately 42 to 55 since 2004 at the four-digit level, but was consistent at approximately 40 from 1992 to 2003. Comparison with aggregated three-digit data shows that the difference in the GL index at the different levels of aggregation is greater than that between Washington and BC. At the three-digit level, the index is around 55 to 65 in the study period. This difference may be explained by the presence of high-value vehicle manufacturing industries, which all have high values of trade and are combined to one industry at the three-digit level. The value of goods data are not adjusted for inflation.

BC and Washington Trade

The industries with the highest average value of trade between Washington and BC from 2001 to 2008 in each direction are shown in Table 1, using the four-digit NAICS code. The upper half shows trade within the main industries crossing from Washington to BC, and the lower half shows trade within the main industries crossing from BC to Washington.



(a)

(b)

FIGURE 2 Annual GL index and value of trade (*a*) between Washington and British Columbia and (*b*) between Michigan and Ontario from 1992 to 2008.

TABLE 1 Highest Average Value Trade Between Washington and British Columbia, 2001–2008

Industry	Value (in millions)	Cumulative %
Washington to British Columbia		
Petroleum and coal products manufacturing	574	20
Motor vehicle manufacturing	199	27
Seafood product preparation and packaging	153	32
Iron and steel mills and ferro-alloy manufacturing	116	36
Plastic product manufacturing	114	40
Pulp, paper, and paperboard mills	113	44
Aerospace product and parts manufacturing	98	47
Converted paper product manufacturing	81	50
Sawmills and wood preservation	74	53
Other general-purpose machinery manufacturing	69	55
British Columbia to Washington		
Oil and gas extraction	1,578	35
Sawmills and wood preservation	427	44
Pulp, paper, and paperboard mills	220	49
Veneer, plywood, and engineered wood product manufacturing	193	53
Electric power generation, transmission, and distribution	138	56
Logging	112	59
Plastic product manufacturing	101	61
Greenhouse, nursery, and floriculture production	92	63
Other wood product manufacturing	78	65
Animal aquaculture	78	66

The average GL index within these industries from 2001 to 2008 is shown in Table 2, sorted by combined value of trade in both directions. The highest value of combined trade (both directions) between Washington and BC is within an industry that is almost entirely interindustry (oil and gas extraction) and that accounts for 35% of goods moved from BC to Washington. Much of this cargo is moved by pipeline, which is not subject to border congestion. As shown in Table 2, the main industry moving goods from Washington to BC is petroleum and coal products manufacturing, which is primarily interindustry as well, having a GL index of 14.64. The industries having high IIT are plastic product manufacturing, other wood product manufacturing, other general-purpose machinery manufacturing, pulp, paper and paperboard mills, and aerospace product and parts manufacturing.

The share of trade moved by truck is also shown in Table 2. The numbers for mode share represent the total annual value of trade crossing each direction between a U.S. state and Canadian province. The data are retrieved from the BTS website. It should be noted that there is a difference in the NAICS and BTS codes definition of oil and gas extraction. Table 2 indicates that trade in this industry is moved by truck and vessel to BC from Washington, while trade within this industry according to the NAICS definition has almost no trade being moved in that direction. The rest of the commodities in Table 2—motor vehicle parts, airplane parts, plastic products, and seafood products—are primarily moved by truck. The industry products having the highest value are typically moved by pipeline and rail between Washington and BC. Pipeline movement experiences no cross-border delay, and congestion-related delay typically affects cross-border rail travel much less than cross-border truck travel.

Ontario and Michigan Trade

The industries with the highest average value of trade between Michigan and Ontario from 2001 to 2008 in each direction are shown in Table 3, at the four-digit level.

TABLE 2 Highest Average Value Trade (Imports Plus Exports) Between Washington and British Columbia and Average GL Index (2001–2008) and Share of Truck in Trade

Highest Value Industry Between Washington and British Columbia (both directions)	GL Index	Total Trade (in millions)	By Truck	
			Northbound (%)	Southbound (%)
Oil and gas extraction	0.42	1,581	22	1
Petroleum and coal products manufacturing	14.64	615		
Sawmills and wood preservation	30.78	501	92	78
Pulp, paper, and paperboard mills	74.34	333	99	71
Veneer, plywood, and engineered wood product manufacturing	25.96	223	79	33
Motor vehicle manufacturing	23.09	218	100	100
Plastic product manufacturing	88.58	214	99	98
Seafood product preparation and packaging	51.84	206	99	99
Aerospace product and parts manufacturing	70.45	143	88	99
Electric power generation, transmission, and distribution	2.79	139	98	97
Other wood product manufacturing	81.33	137	92	78
Iron and steel mills and ferro-alloy manufacturing	19.65	130	84	26
Logging	4.73	115	79	33
Other general-purpose machinery manufacturing	76.39	109	97	81
Greenhouse, nursery, and floriculture production	21.45	102	100	100
Converted paper product manufacturing	35.55	98	99	71
Animal aquaculture	9.35	81	99	99

TABLE 3 Highest Average Value of Trade Between Michigan and Ontario, 2001–2008

Industry	Value (in millions)	Cumulative %
Michigan to Ontario		
Motor vehicle parts manufacturing	8,291	41
Motor vehicle manufacturing	5,123	67
Oil and gas extraction	601	70
Iron and steel mills and ferro-alloy manufacturing	395	72
Resin, synthetic rubber, and artificial and synthetic fibers and filaments manufacturing	327	73
Office furniture (including fixtures) manufacturing	321	75
Other general-purpose machinery manufacturing	318	77
Metalworking machinery manufacturing	312	78
Plastic product manufacturing	294	80
Ventilation, heating, air-conditioning, and commercial refrigeration equipment manufacturing	253	81
Ontario to Michigan		
Motor vehicle manufacturing	29,490	70
Motor vehicle parts manufacturing	4,765	81
Plastic product manufacturing	777	83
Engine, turbine, and power transmission equipment manufacturing	518	85
Iron and steel mills and ferro-alloy manufacturing	508	86
Petroleum and coal products manufacturing	498	87
Office furniture (including fixtures) manufacturing	408	88
Metalworking machinery manufacturing	343	89
Resin, synthetic rubber, and artificial and synthetic fibers and filaments manufacturing	291	89
Other general-purpose machinery manufacturing	251	90

The GL index within these industries from 2001 to 2008 is shown in Table 4, sorted by highest combined value of trade in both directions along with the share of trade moved by truck.

The industry with the highest level of trade is motor vehicle manufacturing. Although the GL index is only 29.71, the value of trade is an order of magnitude larger than the largest industry between Washington and BC and is larger than trade within any other industry. The second-highest industry, motor vehicle parts manufacturing, is closely related to the first. The IIT level within this high-value industry is significant: 73.07. All of the industries but one on the list are manufacturing industries, and the nonmanufacturing industry has a low level of IIT.

RELATIVE IMPACT OF BORDER DELAY

To evaluate the relative impact of border delay when experienced within the Cascade gateway or the Great Lakes gateway, data on truckloads and total values were obtained from the BTS website. These data are available only for trucks entering the United States. The analysis revealed that the average value of each loaded container in 2008 is much lower for trucks entering the United States from BC to Washington (around $19,000) than for trucks moving from Ontario to Michigan (around $32,000 per container). The proportion of empty containers entering Washington from BC is also higher (31%) compared with those moving from Ontario to Michigan (14%). The value of trade within industries also provides useful information for this analysis. The average value of containers carrying a commodity compared with the value per weight unit of those goods, along with the proportion of empty trucks crossing, allows us to make assumptions on the utilization of trucks.

The BTS website does not provide data on the number of trucks carrying a specific commodity. However, by dividing the value of the total trade within a specific commodity by the total weight of the same commodity, the average value per unit weight can be calculated and used to estimate the cost of in-transit inventory caused by delay. The weighted average (by value) U.S. dollar value per pound of the main commodities crossing by truck is $0.73 for trade between Washington and BC, but $6.83 between Michigan and Ontario. The Great Lakes gateway also trades most heavily within those industries that are highly dependent on truck transportation.

The study by the Conference Board of Canada previously discussed listed the seven industries most vulnerable to border delay (*14*). These industries were chosen mainly because they have a large share of trade and are dependent on truck transportation. Of the two state–province partnerships analyzed here, the one between Michigan and Ontario displays the most trade within these seven industries, which accounts for 79.5% of the total trade. Between Washington and BC, trade within these industries accounts for 9.6% of the total trade. In most cases, the IIT levels within those industries most vulnerable to border delay are high.

CONCLUSIONS

Specialization, labor costs, and low transportation costs have resulted in increased intra-firm relationships on either side of the U.S.–Canada border and stable IIT corridors. Border delays are costly; they inhibit trade, reduce transportation system productivity, and raise transportation costs for companies that regularly need to transport goods across the borders. At the Michigan–Ontario border, high levels of IIT are observed that are carried out by trucks and mainly consisting of trade in horizontally differentiated goods. Because the majority of the trade relies on truck transportation for door-to-door delivery, these corridors are stable truck transportation corridors, with movement of goods not likely to shift modes. Border delay has significant cost implications for these corridors because disruptions are amplified down the supply chain, and just-in-time operational practice implies greater consequences of delay.

Washington and BC have less integrated trade. In addition, much of the trade occurs via pipeline and rail, which experience less border congestion. Relative to the eastern crossings, the same amount of border delay has smaller economic consequences within the western corridor, although these consequences are still significant from the perspective of regional economic development. Trade in this region mainly consists of stable interindustry trade and trade of vertically differentiated goods, meaning that the reciprocal trade that does occur is not within highly integrated supply chains. In this area, goods might be difficult to acquire from other sources: areas of low economic activity lie to the east, and the Pacific Ocean lies to the west. Solutions to border delays in the western corridors

TABLE 4 Highest Average Value Trade (Imports Plus Exports) Between Michigan and Ontario and Average GL Index (2001–2008) and Share of Truck in Trade

Highest Value Industry Between Michigan and Ontario (both directions)	GL Index	Total Trade (in millions)	By Truck	
			Northbound (%)	Southbound (%)
Motor vehicle manufacturing	29.71	34,613	76	56
Motor vehicle parts manufacturing	73.07	13,056		
Plastic product manufacturing	55.31	1,070	98	91
Iron and steel mills and ferro-alloy manufacturing	87.47	903	98	76
Office furniture (including fixtures) manufacturing	87.77	729	99	99
Engine, turbine, and power transmission equipment manufacturing	49.96	691	98	99
Metalworking machinery manufacturing	92.98	655	98	99
Resin, synthetic rubber, and artificial and synthetic fibers and filaments manufacturing	73.12	618	92	100
Petroleum and coal products manufacturing	35.35	610	5	6
Oil and gas extraction	1.93	603		
Other general-purpose machinery manufacturing	85.63	569	97	86
Ventilation, heating, air-conditioning, and commercial refrigeration equipment manufacturing	54.28	339	99	99

should mainly be concentrated on increasing truck transportation efficiency.

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Documenting Truck Activity Times at International Border Crossings Using Redesigned Geofences and Existing Onboard Systems

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When crossing international gateways, commercial vehicles engage in multiple activities—such as approaching on congested roadways, paying tolls, undergoing customs inspections, and waiting in queues—that increase trip times and trip-time variability. Documenting the times incurred in these multiple activities is difficult because the activities are spatially dispersed, temporally variant, and affected by institutional and operational complexities resulting from the multiple organizations operating infrastructure in two countries. An approach is presented to capture the times required to complete various activities at international border crossings, using trucks from a large fleet that regularly crosses international gateways. This approach takes advantage of the telematics systems already in use by the truck fleet and is not dependent on installation of roadside equipment. Geofences are specified at strategic locations that delineate the beginnings and ends of activities of interest and send information electronically to the vehicles' onboard data units. The activity times for an individual truck crossing can be determined from data automatically recorded when trucks enter and exit the specified geofences. The trucks serve as activity time probes, and the activity times of multiple trucks can be aggregated to form activity time distributions. To demonstrate the capabilities and potential of the approach, empirical data from a large fleet of trucks traversing two of the busiest U.S. border crossings are used to produce results on median crossing times, variability in trip times, time-of-day patterns, and excess times (i.e., delays) generated from customs inspections and the queuing that results from the inspections.

Documenting the travel times that trucks incur when crossing an international border facility or gateway is of interest to the private freight industry and to gateway facility operators and planners. Private carriers and shippers can benefit from having objective travel time measures for trip planning and scheduling or even for choosing among alternate routing options. By monitoring trends in the documented travel times, facilities operators and planners can detect when conditions have changed enough to warrant changes in infrastructure or operations. In addition, developing, calibrating, and validating predictive models of how travel times respond to alternate infrastructure configurations or operations policies requires extensive and valid data on crossing times.

To document travel time accurately, a method is required for collecting adequate and representative crossing-time data. Contributing to the magnitude of and variability in truck crossing times are the multiple activities involved with international truck crossings: approaching the gateway on freeways or surface streets, paying tolls, waiting in queues, undergoing customs inspections, and possibly visiting duty-free facilities. Accordingly, the data collection task would be enhanced if the times incurred in these various activities could be obtained. Decomposing the overall travel time into its components can identify the critical activities that affect the overall time and allow for development of more behaviorally responsive models. For example, studies that predict the effects of increased demand would require an understanding of the impact of the interaction between customs screening or toll collection rates and traffic volumes in producing queuing-induced delays. It would be helpful for planning purposes to be able to control overall crossing times for voluntary activities, such as visiting duty-free facilities, before using empirical crossing times to represent conditions at a border-crossing facility. Similarly, carrier management may wish to monitor the participation of its trucks in these voluntary activities to ensure that they are not contributing to reduced productivity.

This paper describes an approach to document truck activity times associated with an international border crossing by using technologies that are already in use by truck fleets. The approach relies on Global Positioning System (GPS) technology, virtual perimeters called "geofences" that surround areas of interest, and a mechanism for data transmission. This approach needs no roadside infrastructure and is thus easy to implement, as long as fleet operators are willing to share data. The approach is also rapidly reconfigurable, which is attractive when infrastructure at the gateway changes (e.g., during and after infrastructure rehabilitation or expansion).

Traditional methods of collecting crossing-time data involve locating personnel or surveillance technologies, such as license plate readers, at locations on both sides of the border. The times that trucks cross the surveillance locations are recorded, along with information that allows data records collected at the surveillance

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locations to be matched with an individual truck trip. The time between the matched data records yields the truck time between the locations (*1, 2*).

Using traditional travel time methods is complicated at international crossings because the various activities that take place at the crossings involve infrastructure and operations associated with multiple agencies (some private, some public) in two countries. Moreover, the spatial extent of the multiple activities and the temporal variability in the activity times make it difficult to obtain representative activity time data. Times are obtained only between the fixed surveillance locations. To collect times for all the activities of interest, an extremely large amount of equipment or personnel must be deployed. Personnel and even equipment used for project-level studies can be stationed only for relatively short periods of time, and this limitation does not allow long-term trend monitoring to take place and can lead to unrepresentative samples over time. New technologies (such as radio frequency identification or Bluetooth readers) used to detect the time that a truck passes a fixed location make it easier to reidentify the truck at a downstream surveillance location (*3*). However, these technologies suffer from the same difficulties as traditional methods in decomposing times into multiple activities, as do GPS-based approaches that try to decompose individual activities by imposing geofences after the fact (*4*).

Some recent efforts are using Bluetooth technology to measure crossing times by employing geofences in a manner similar to that presented in this paper (*3*). The primary differences lie in the use of roadside infrastructure and the transmission of data. Other approaches attempt to detect mobile devices (such as cell phones) that possess a unique media access control address at multiple points in space and time (*5*). This paper does not argue for the superiority of one method over the other. Rather, it illustrates the type of results that can be obtained with a geofence-based approach, whether the approach uses Bluetooth devices, the technology discussed in this paper, or some other approach.

An overview of the geofence approach is provided next, with an emphasis on redesigning existing geofences to allow collection of data on activity times at international crossings. Illustrations are provided for an implementation designed to collect activity times from a large truck fleet at two of the busiest international commercial vehicle crossings in the United States: the Ambassador Bridge and Blue Water Bridge crossings. The Ambassador Bridge is a privately owned and operated facility that connects Windsor, Ontario, and Detroit, Michigan. The Blue Water Bridge is a publicly owned and operated facility that connects Sarnia, Ontario, and Port Huron, Michigan. Using geofences designed by the authors, empirical data were collected at these crossings and processed to provide results that illustrate the types of information that can be obtained. These illustrative results are presented along with reflections on the potential of the approach.

GEOFENCE-BASED APPROACH

The approach considered in this paper is based on exploiting the existing hardware, software, and communication capabilities of a GPS-based onboard data unit (OBDU) already in use on fleets of trucks. These systems automatically record and communicate time-stamped truck locations when events of interest occur. For example, the freight hauler cooperating in this study uses a system that sends a data record from each of its trucks when a truck's ignition is turned off or on, when the truck travels faster than some threshold speed, when no record has been received in some predetermined time interval, when the truck has not moved in some specified time interval, or when any of a number of several other defined events occur. Each data record includes a time stamp, latitude, and longitude, as well as a vehicle identifier, the instantaneous speed at the time of the event, an odometer reading, the heading, textual information on the type of event that triggered the ping (e.g., ignition on, time send), and several other data fields.

Of interest in this paper are the records triggered when the truck—or more correctly, when the OBDU—crosses an electronic geofence. A geofence is the virtual perimeter of an area (a polygon) that defines a region of interest (ROI). The coordinates of the points that define the geofence are remotely transmitted to the OBDU. The unit continuously checks GPS location signals against the electronic geofence boundary to determine if the truck entered or exited a geofenced polygon. Once the OBDU determines that it has entered or exited a geofenced polygon, a crossing data record is transmitted to a database with the type of information described above. The recorded data includes the time stamp and name of the geofence crossed and an indication of whether the crossing was into or out of the polygon.

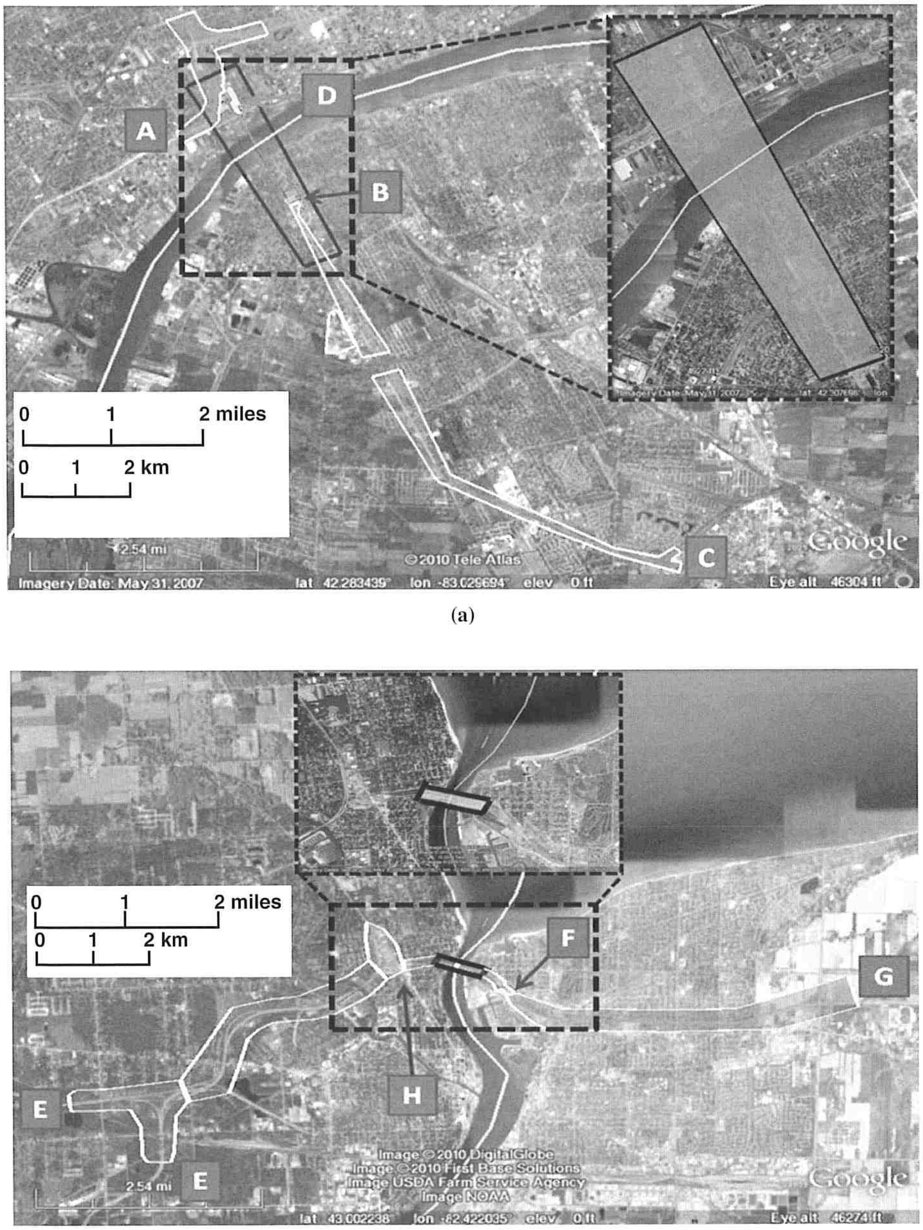
By using the unique identifier of the truck (through its OBDU) included in the data records and additional logic, analysts can identify and examine records for the various geofences crossed during an individual truck trip and the direction of crossing. These matched records form a chained trip. By taking the difference in crossing times for a pair of crossing records in the chained trip, the travel time between the corresponding locations is determined. Thus, specifying geofences at strategic locations that delineate important activities yields the travel time between these strategically selected locations, and the times incurred in the activities can thus be determined.

Before the work reported here, the freight hauler providing empirical data for this study had implemented a single geofence per international crossing that provided an alert when its trucks were in the vicinity of the crossing. At the Ambassador Bridge and Blue Water Bridge crossings used in the empirical study, the company's geofences were centered at the U.S.–Canadian border and covered limited areas, as depicted by the black rectangles in Figures 1*a* and 1*b*. (The inlays are magnified in Figure 1 to represent their detail.)

For this study, additional geofences were specified at selected activity locations. To implement these refined geofences, the polygon boundaries were digitized on top of aerial photography and satellite imagery using a combination of available GIS products. These new fences were then transmitted to the OBDUs in the vehicles via cellular communication channels.

The difference in the spatial extent of the area covered by the geofences previously implemented for company purposes and those implemented for this study using the existing systems can be seen in Figures 1*a* and 1*b*. In addition to the previously implemented fences illustrated by the black rectangles, the other polygons in the figure represent the locations of the multiple newly designed geofences. (The labels of locations are used to describe empirical results in the next section and are discussed at that point.) The new sets of geofences include road distances of more than 16 km (10 mi) around each international crossing, compared with the approximately 4.2 km (2.6 mi) and 0.90 km (0.56 mi) covered by the previously existing fences at the Ambassador Bridge and Blue Water Bridge crossings, respectively.

The spatial detail obtained with the redesigned geofences is illustrated by the examples depicted in Figure 2. Figure 2*a* depicts the geofence surrounding the duty-free area (dashed inlay) for trucks


A
B
C
D
0 1 2 miles
0 1 2 km
2.54 mi
©2010 Tele Atlas
Imagery Date: May 31, 2007
lat 42.283439° lon -83.029694° elev 0 ft
Eye alt 46304 ft
Google
E
E
F
G
H
0 1 2 miles
0 1 2 km
2.54 mi
Image © 2010 DigitalGlobe
Image © 2010 First Base Solutions
Image USDA Farm Service Agency
Image NOAA
lat 43.002238° lon -82.422035° elev 0 ft
Eye alt 46274 ft
Google

(a)

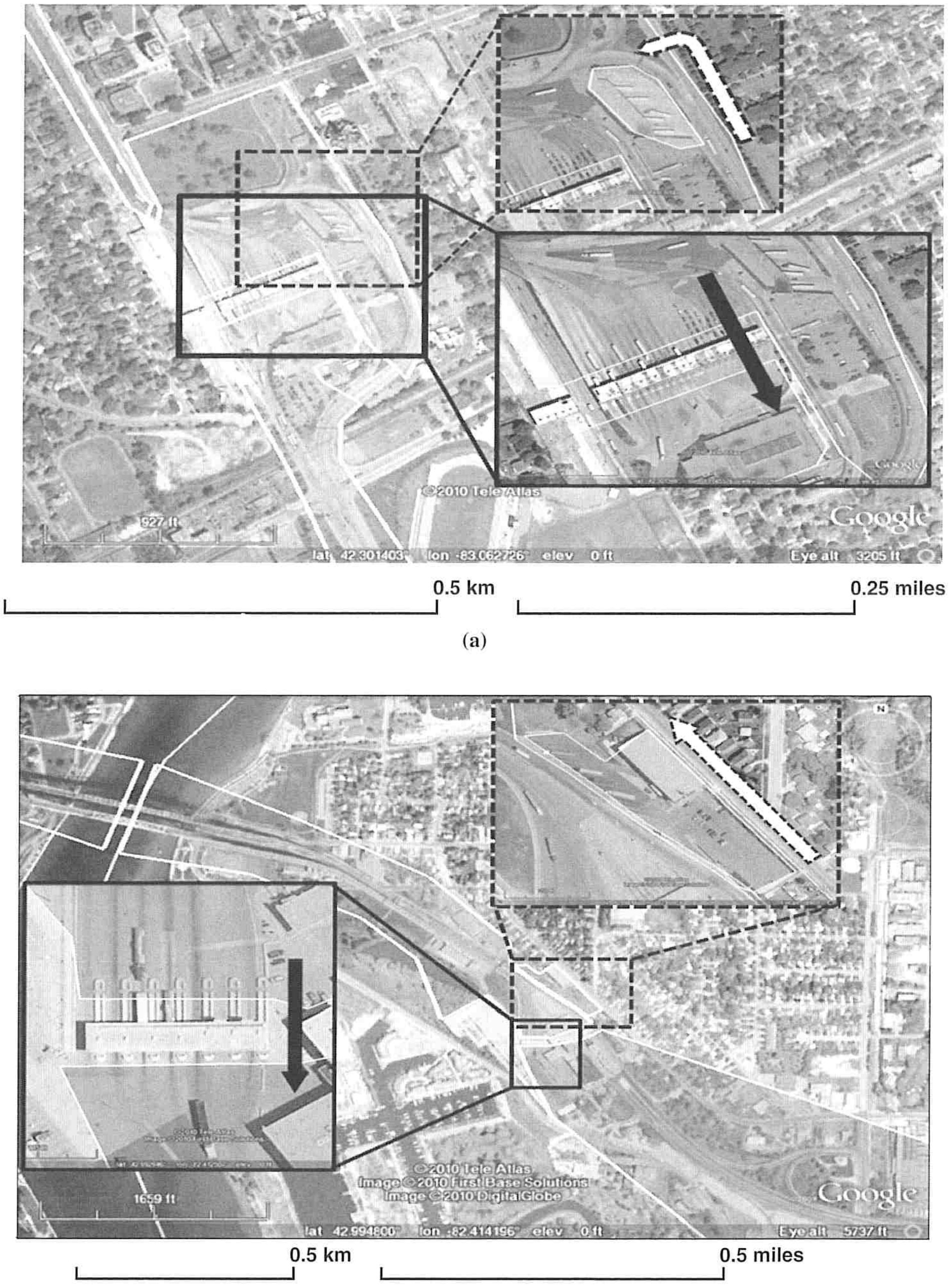
(b)

FIGURE 1 Illustration of geofence locations previously in operation for company purposes (black rectangle) and newly implemented geofence locations (solid white polygons) used to track activity times; inlays (marked by dashed lines) are magnified views of previously implemented geofences: (*a*) Ambassador Bridge crossing and (*b*) Blue Water Bridge crossing.

entering the United States at the Ambassador Bridge crossing, as well as the geofences used to delineate the Canadian customs screening station at the crossing (solid inlay). The corresponding illustrations for the Blue Water Bridge crossing are presented in Figure 2*b*.

EXTRACTION OF TRUCK ACTIVITY TIMES: ILLUSTRATIVE RESULTS

The illustrative empirical results presented in this section were derived from the freight hauler's data records collected between July 29, 2008, and June 18, 2009. The records covered much of the United States and Canada. To reduce the size of the data sets, a large ROI was selected as a super geofence that covered all geofences around each crossing, and records outside of the ROIs were filtered out. Some of the remaining records, including records generated from geofence crossings, occurred on trips that did not cross the border. Any trip that did not cross the border within predetermined time and distance thresholds was considered as a domestic trip, and its records were also eliminated from consideration. The remaining geofence crossing records, except for a small number of records filtered with "data cleaning methods" described in the Discussion section, were used in the analysis reported here. More details about the extraction of relevant records can be found elsewhere (*6*).



(a)

(b)

FIGURE 2 Illustration of spatial resolution of new geofences: duty-free facilities location (dashed inlay) and customs screening location (solid inlay): (*a*) Ambassador Bridge crossing and (*b*) Blue Water Bridge crossing.

The records for geofence locations indicated in Figure 1 were matched to produce "crossing time" distributions. Specifically, referring to Figure 1*a,* records indicating an "in" crossing at A (C) were matched with records indicating an "out" crossing at B (D) to determine the time required to cross from the United States to Canada (and from Canada to the United States) at the Ambassador Bridge. Similarly, "in" crossing records at the fence indicated by E (G) in Figure 1*b* were matched with "out" crossing records at F (H) to determine the time to cross from the United States to Canada (and from Canada to the United States) at the Blue Water Bridge. There are other origin points of interest for trips in both directions at the Ambassador Bridge (Fig. 1*a*) with different characteristics that can be addressed in a similar fashion, but presentation of the empirical results is not necessary for the illustrations of this paper. At the Blue Water Bridge (Fig. 1*b*), the limited access of Highway 402 covering the polygon beginning at location G restrains the entry points for U.S.-bound traffic. There are two important access locations for Canada-bound traffic at the Blue Water Bridge crossing, indicated by the two "E" locations, but the crossing times are similar for the trips entering these two locations, and the results are pooled in the empirical results presented in this paper. In this way, the illustrative empirical results relate to homogeneous traffic patterns.

The 50th percentile (median) and 90th percentile values of the distributions of the thousands of crossing times, as defined above, by bridge facility (Ambassador Bridge or Blue Water Bridge) and direction (into the United States or into Canada) are presented in the Table 1 columns denoted "original distributions." The median distances traveled between the specified fences, as obtained by odometer readings in the data records, are also presented.

Uncertainty in crossing times can be more onerous to shipment planning than increases in crossing time that are known in advance, especially for shipments serving scheduled production runs using just-in-time delivery schemes. The uncertainty in predicting the crossing time of a random truck is captured by the difference in the 90th percentile and 50th percentile values. The difference, which is similar to the so-called buffer measure, represents the spread or variability in the distribution (*2, 7*). It is more useful than the standard deviation in depicting variability in highly skewed distributions with much longer right tails than left tails. These variability measures are also presented in Table 1.

The duty-free polygons can be used to determine if a truck visited the duty-free area on its trip and the amount of time a truck spent in the area. The fleet operator has found this information to be useful for fleet management. In this paper, the interest lies in the importance of capturing these voluntary diversions in an attempt to diminish their effect on crossing-time distributions. As seen in Figure 2, the present sets of implemented geofences allow U.S.-bound trucks entering the duty-free areas at either crossing to be identified. (Redesign of the fences to allow such identification for Canada-bound trips is presently under consideration.) In the data set used to develop the "original distributions" summarized in Table 1, the percentages of the U.S.-bound truck trips passing through the duty-free fences at the Ambassador Bridge and the Blue Water Bridge crossings were different. The crossing-time statistics, after deleting these trips, are presented in the columns of Table 1 denoted "without duty-free trips." Comparison with the corresponding "original distribution" values shows a noteworthy decrease in crossing times and variability of these times at the Blue Water Bridge when controlling for these "voluntary diversions." The difference between the original and refined values supports the utility of being able to identify such events when attempting to develop representative values of crossing times for trips trying to cross the border expeditiously.

The crossing-time percentile values indicate the type of information that can be provided for fleet planning and analysis. Indeed, the fleet manager and one of the major shippers using this freight hauler commented on the difference between a similar set of geofence–derived values (determined from a smaller set of data collected earlier) and what they had been assuming at one of the crossings. They expressed more confidence in the geofence-derived data than in their prior impressions, which had been based partly on anecdotal evidence. (It was noted to these individuals that the data should be used with caution at this point, both for the reasons presented in the Discussion section and because the individuals were tending to focus on median times rather than upper percentile times, which should also be considered for planning purposes. Again, the values are presented here only to indicate the type of empirical results that can be obtained, and the reader is cautioned against applying these values to real-world situations.)

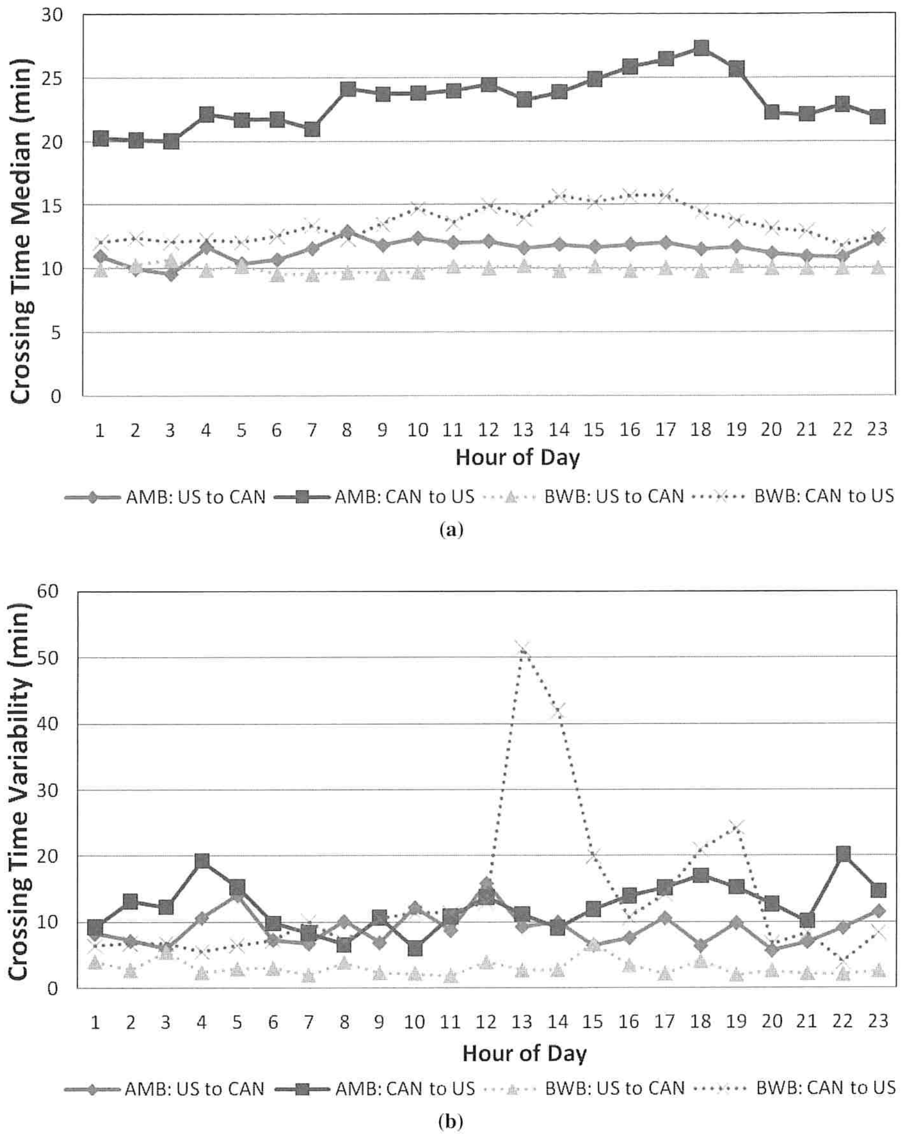
The percentile values in Table 1 are difficult to compare across bridge–direction pairs because the types of roadway traversed and the distances traveled vary by bridge and direction. However, the variability in the values is more comparable. These values indicate that the crossing times are much more variable for trips entering the United States than for trips entering Canada at both crossings. These results are consistent with expectations of those familiar with truck shipments at these crossings and provide a general validation of the approach.

The data can also be used to investigate temporal differences in crossing times. In Figure 3, the median (50th percentile values) and variability measures (90th percentile minus the 50th percentile) by hour of day are plotted for the four bridge–directions. Again, the results are intended to illustrate only the types of results that can be obtained; more in-depth analysis is needed before the time-of-day patterns could be considered fully representative. (For example, the high variability measures for U.S.-bound trips at the Blue Water Bridge crossing at 13 H and 14 H are surprising. Upon investigation, they do not appear to be associated with small sample sizes, but additional investigations are underway to confirm the validity of these values.) However, even taking a cautious approach, the plots provide a strong indication that time-of-day trends can be captured by this approach and that these trends may vary by bridge and direction.

With additional processing, the data can also be used to determine times in excess of free-flow time to give an indication of the delays caused by infrastructure, traffic congestion, or operational features. The excess time a truck incurred on a trip between a pair of geofence

TABLE 1 Illustrative Crossing-Time Statistics by Bridge and Direction

	Original Distributions				Distributions w/o Duty-Free Trips	
	Ambassador Bridge Crossing		Blue Water Bridge Crossing		Ambassador Bridge Crossing	Blue Water Bridge Crossing
	United States to Canada	Canada to United States	United States to Canada	Canada to United States	Canada to United States	Canada to United States
Number of records	4,215	5,401	2,613	2,736	4,840	1,946
Median (50th percentile) distance [km (mi)]	4.34 (2.70)	15.62 (9.70)	9.98 (6.20)	9.43 (5.86)	15.62 (9.70)	9.43 (5.86)
Median (50th percentile) time (min)	11.70	24.60	9.98	14.68	23.98	13.43
90th percentile time (min)	20.03	38.45	12.70	30.63	37.03	25.32
Time variability (90th percentile – 50th percentile) (min)	8.33	13.85	2.72	15.96	13.05	11.88



(a)

(b)

FIGURE 3 (*a*) Crossing-time medians for bridge–direction pair, by hour of day, and (*b*) crossing-time variability for bridge–direction pair, by hour of day.

crossing records is determined by subtracting the free-flow time for the roadway segment between the locations corresponding to these records from the actual time the truck incurred on the trip between the crossing records. The actual time the truck incurred is determined from the records in the manner presented above. The free-flow time is the time that the truck would incur traveling over the roadway if there were no impediments such as customs inspection or toll collection facilities, traffic control devices, or traffic congestion.

The free-flow time is determined by dividing the distance the truck traveled between the crossing records by the free-flow speed for the roadway segment between these records. The distance traveled is obtained by subtracting the odometer distances in the data records. The free-flow speed could be determined in a variety of ways, and future work could be devoted to comparing alternative approaches and specifying a preferred method. In this analysis, the truck speeds that appear in the data records were used to determine the free-flow speeds. Specifically, when considering an uninterrupted roadway segment, the 85th percentile values of the speeds in the geofence crossing records on the roadway were used. The 85th percentile speed was considered because of its common use in traffic engineering and was selected as appropriate for first-cut analysis after investigation of the empirical distributions of truck speeds in the data records. Free-flow speeds on adjacent segments were averaged to determine the free-flow speeds of roadway segments where flow would be interrupted (e.g., by customs screening).

The summary statistics of excess times, by bridge–direction pair, on segments between the first geofence upstream of the primary customs screening location and a geofence approximately 1 km (0.6 mi) further upstream are presented in Table 2. Because the first fence upstream of the customs screening location is placed very close to the screening facility (see Figure 2), the excess times determined in this way would primarily be caused by traffic queuing upstream of the customs

TABLE 2 Illustrative Queuing-Induced Excess Time Statistics for Roadway Segments Upstream of Customs Screening Locations by Bridge and Direction

	Queuing Induced Excess Time			
	Ambassador Bridge Crossing		Blue Water Bridge Crossing	
	United States to Canada	Canada to United States	United States to Canada	Canada to United States
Number of records	6,869	5,721	2,652	1,974
Median (50th percentile) distance [km (mi)]	1.30 (0.81)	1.00 (0.62)	1.14 (0.71)	0.97 (0.60)
Median (50th percentile) time (min)	0.78	3.67	0.46	2.13
90th percentile time (min)	5.53	14.88	1.86	12.18
Time variability (90th percentile – 50th percentile) (min)	4.74	11.21	1.40	10.05

facilities. (At times, queues extend farther than 1 km upstream. The excess times in these segments can be found by using fences further upstream in a similar manner.) The results indicate markedly longer queuing-induced excess times and more variability in the excess times for trips entering the United States than for trips entering Canada, regardless of which crossing is used.

For each bridge–direction, the first geofence upstream of the customs screening station and the first fence downstream were intentionally placed close to the station (see Figure 2). The records for these fence crossings were matched to produce the times incurred when trucks traversed the segments that included customs screening. By subtracting free-flow times, as discussed above, the excess times on these segments were determined. These excess times would primarily result from customs screening time and the increased times resulting from decelerating to and accelerating from the stop required for inspection. As a result, the data can provide information on the additional times resulting from customs screening. The summary statistics for these screening-induced excess times are presented, by bridge–direction pair, in Table 3. As with the queuing-induced excess times in Table 2, the screening-induced excess times and the variability in the times are greater when entering the United States than when entering Canada, regardless of the crossing. Indeed, the increased screening-induced times would suggest longer inspection times when entering the United States than when entering Canada. In queuing-theory language, these longer service times are a likely contributor to the longer queues and delays, assuming that arrival rates are roughly similar. (Small differences in service times can lead to relatively large differences in delays if the demand is sufficiently high.)

DISCUSSION OF RESULTS

The empirical results presented are intended to illustrate the type of information that can be amassed from the geofence-based approach. They should not be considered as representative empirical data. The current geofences allow the crossing-time distributions to be controlled for extra duty-free time for U.S.-bound trips but not for Canada-bound trips. Additional data-cleaning methods, the description of which is beyond the scope of this paper, have also been used to account for the times incurred when trucks are sent to secondary customs inspection or when drivers decide to voluntarily stop at the side of the road at locations between the first and last geofence considered when determining crossing times. More systematic investigation is required to ensure that most if not all these trips have been identified. The relatively small number of these trips identified makes it unlikely that a large enough number of these trips remains in the data to strongly influence the crossing-time statistics presented in Table 1. Nevertheless, there could be other as-yet undetermined activities that could eventually be controlled for, in an attempt to increase the representativeness of the reported activity time data in indicating the distribution of direct crossing times.

TABLE 3 Illustrative Customs Screening-Induced Excess Time Statistics by Bridge and Direction

	Screening Induced Excess Time			
	Ambassador Bridge Crossing		Blue Water Bridge Crossing	
	United States to Canada	Canada to United States	United States to Canada	Canada to United States
Number of records	6,826	4,840	2,613	1,946
Median (50th percentile) distance [km (mi)]	0.05 (0.03)	0.02 (0.01)	0.03 (0.02)	0.04 (0.02)
Median (50th percentile) time (min)	1.10	1.22	0.93	1.46
90th percentile time (min)	1.94	2.36	1.42	2.93
Time variability (90th percentile – 50th percentile) (min)	0.84	1.14	0.49	1.47

The empirical results should also be considered with caution because they are derived from only one freight hauler's fleet. Based on available truck volume data by bridge–direction, the number of chained trips used to produce the empirical results represents approximately 1% of the total truck volume during the analysis period. This may seem like a small sample compared with traditional studies that use vehicles as "probes" of roadway conditions and that have sample rates that are often as high as 3% (*8*). However, traditional studies tend to consider sampling conditions over a network of roadways, whereas the emphasis here is on sampling conditions on a constrained linear corridor. In these conditions, only a few observations can be fairly representative of travel times, especially when there is limited vehicle passing. Moreover, it is expected that, in the future, more fleets will use technologies similar to those exploited in this study, and the potential for data availability will increase.

Potential selection bias in the observations may be of more concern than a low sampling rate. The fleet of trucks from which the data were collected were all Free and Secure Trade (FAST) certified (*9, 10*). Because this firm's cargo meets the "low risk" criteria of the FAST program, its trucks would tend to receive expedited customs screening. Consequently, the empirical results obtained from these probes may not be representative of all trucks using these border crossings. However, for all activities in the trip other than the primary inspection activity, FAST and non-FAST trucks would be expected to behave similarly, and the times would be good indicators of all but the screening-related activity time. For screening-related times (Table 3), the information should still be useful in representing the FAST-certified segment of the border-crossing population. The authors are presently investigating this assumption in a field validation study.

Caution in drawing general conclusions from the empirical results is also advised because the results are compiled from only slightly more than 10 months of data. Although 10 months is a relatively long duration for border-crossing travel-time studies, and the number of records is relatively high, the numerical values could be influenced by the poor economic conditions during this period or by the Ambassador Bridge Gateway Infrastructure project that has been underway since January 2008 (*11*). Moreover, the empirical times reported in this paper are likely to be heavily influenced by traffic volumes and the number of customs inspection lanes open at the times of the truck crossings. These variables would likely differ by bridge-crossing pair and time of day and day of the week, as would the numbers of empirical truck observations available. Controlling for these variables is a topic for future research (which is presently underway), but these variables are mentioned here to reemphasize the caution that must be used in drawing conclusions from the empirical results presented in this paper.

Although they are not definitive, the empirical results presented indicate the types of results that can be obtained from the geofence-based approach. The general patterns indicated (e.g., longer queuing-induced delays when entering the United States than when entering Canada) support prior expectations, indicating the potential of the approach to provide valid quantitative measures of the times involved with the multiple activities occurring at border crossings.

The geofence-based approach is also attractive because it takes advantage of hardware, software, and communications systems that are already being used by existing truck fleets. Thus, data can be collected over long stretches of time rather than only during a specific study period, and the approach lends itself to effective long-term monitoring. Moreover, the approach incurs only the marginal costs associated with increased data transmission and storage. In the empirical study presented here, the more intensive monitoring of border-crossing activity times through implementation of multiple new geofences has been conducted easily within the existing data transmission costs of the freight hauler's truck-tracking efforts.

In addition, because no roadside hardware is required, data can be collected on multiple activities without having to negotiate institutional barriers that may be imposed by the multiple agencies and industries operating the border-crossing infrastructure and facilities. When the layout of a gateway changes (e.g., when a new duty-free facility is installed or when the configuration of an approach roadway is changed), new geofences can be designed and implemented quickly via the OBDUs. No reconfiguration or reinstallation of roadside infrastructure is required.

However, to be useful for monitoring transportation facilities, the approach requires that the shippers and carriers with existing systems share data on the movement of their trucks. Using this approach for more than the proof-of-concept–type studies reported here would require public–private data-sharing agreements. The success of present initiatives underway will indicate whether the carriers see sufficient benefits in receiving accurate data on overall crossing times or on the times their own trucks spend in voluntary activities to make such agreements sustainable (*3*). Of course, it will be easier to ensure extensive temporal coverage from such agreements at international crossings used regularly by a few large fleets. Indeed, the Ambassador and Blue Water Bridge crossings, which formed the basis of this study, are regularly and repeatedly crossed by relatively large and technologically advanced fleets of trucks serving the auto industry. At crossings such as these, data from just one or two fleets might provide sufficient temporal coverage of activity time patterns.

It is presently planned to extend the data collection and type of analyses reported here to longer periods of time and other activities, to assess the representativeness of the results obtained and to understand any biases that may exist, and to refine geofence specifications in response to results obtained. The potential of redesigning geofences and taking advantage of the existing OBDU systems carried on truck fleets to document truck activity times is attractive. It is hoped that further studies, such as those presently planned here and elsewhere, will refine the methodological issues and increase the likelihood of using this or a similar approach as an ongoing tool for collecting truck activity times at international crossings (*3*).

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The International Trade and Transportation Committee peer-reviewed this paper.

Macroeconomic Effects of Road Corridor Investment in Kazakhstan

General Equilibrium Perspective

Olly Norojono, David Roland-Holst, and Guntur Sugiyarto

Infrastructure development across Central Asia facilitates connectivity, competitiveness, productivity, and ultimately economic growth and regional integration. A sample development project is a large road corridor in Kazakhstan. This report shows the economic impact of such a project. The quantitative work follows a dynamic general equilibrium model covering both direct and indirect effects, including trade facilitation, transport cost reduction, and increased productivity. The cumulative indirect impacts benefit Kazakhstan and the many economies linked to it.

As Asian economic integration advances, infrastructure challenges arise. Asia's growth has been indirectly associated with maritime trade routes established centuries ago. More recently, this growth has been driven by other transport modes, including road, rail, and air travel. Energy trade is also an important variable. This paper presents a forward-looking economic model that is used to determine the impact of significant infrastructure projects in Central Asia and beyond.

Previous experience in this area indicates that a well-developed economic model can elucidate the many indirect benefits of large infrastructure projects and regional trade facilitation initiatives (*1–3*). Such a tool can capture myriad indirect effects, including ones arising from regional integration. It can also better identify the efficiency and growth dividends for diverse stakeholders. With stronger evidence of benefits for such projects, particularly with respect to regional development and poverty reduction, policy makers can better justify their appropriate fiscal commitments and promote complementary bilateral–multilateral facilitation agreements.

If Central Asian countries are to realize their full economic potential, more effective trade integration within the region and the rest of Asia is essential (*4, 5*). Currently, these economies have limited demand levels because of their low average incomes and because their production structures are heavily specialized in primary commodities. To take full advantage of external markets that can expand demand for the countries' products and diversify consumption, more extensive and efficient transportation networks are being planned and constructed. This paper presents multicountry estimates of the potential national and regional growth benefits of sustained commitments to such investments.

Ultimately, the gains from regional trade and transport development depend on the complex interplay of market forces, responses from households and firms to changes in the policy environment and market conditions, direct and indirect linkages among various sectors of the economy, and backward and forward linkages between the domestic economy and the rest of the world. Currently, there are no tools that would enable the policy makers in this region to make informed decisions on these issues. To overcome this limitation, a Central Asia Computable General Equilibrium (CA-CGE) model has been developed. This dynamic, multicountry CGE model links Central Asian countries directly to their key trading partners. The modeling results can inform more effective regional policy and multilateral dialogue in several ways for Central Asia, and may help policy makers to do the following:

- Assess effects of policy reforms in individual countries, including their effects on poverty and inequality (*6, 7*);
- Analyze the economywide and cross-border effects of major investment projects affecting the region, especially the projects that reduce trade costs for these countries (*8, 9*);
- Assess the effects of regional cooperation and integration initiatives;
- Make economic projections for individual countries; and
- Analyze economic and resource linkages (including energy) among countries in the region, and among them and other countries.

In its present form, the CA-CGE model includes Kazakhstan, the Kyrgyz Republic, the Xinjiang Autonomous Region of China, the rest of China, Russia, and the rest of the world. China has become an important trading partner for the Central Asian countries, with Xinjiang accounting for the bulk of China's trade with the Central Asian countries. Russia remains a leading trading partner for all Central Asian countries. It is also the main destination country for migrant workers from Central Asia. The base year for the model data is 2004. Subsequently, the model could be extended to include other neighboring countries and their trading partners.

TRANSBOUNDARY IMPACTS

Project

Infrastructure and other projects across the Central Asian region facilitate economic growth and regional integration. Included among these projects is a large road network project or corridor in Kazakhstan connecting Khorgos (a border town between Kazakhstan and China),

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Almaty, Shymkent, and Aktobe (a border town between Kazakhstan and Russia). As Figure 1 indicates, this project involves not only many regions of this country (the world's seventh largest by land area), but also its major trade routes to neighboring and more distant trading partners. As with many large projects, the costs and benefits of this project will be complex and will be dispersed over time and across domestic, regional, and even global stakeholder groups. Using the new modeling facility, this paper examines the growth and other key effects of the project over the period 2008–2030.

The Kazakhstan road corridor project is very large, involving a total investment of about 7% of the country's 2007 gross domestic product (GDP). The economic value of the transport and distribution services that this corridor will provide, including collateral investments around the corridor, will grow in both absolute and relative terms to the rest of the country, where infrastructure services are generally inferior. The primary objective of this analysis is to elucidate the complex and far-reaching indirect effects that this project will have on economic growth across Kazakhstan, the Central Asia Republics (CAR), and even more distant regions.

Modeling Approach

The complexities of today's global economy make it very unlikely that policy makers relying on intuition or "rules of thumb" can achieve optimal economic results in domestic or international arenas. Market interactions are so pervasive in determining economic outcomes that more sophisticated empirical research tools are needed to improve visibility for both public- and private-sector decision makers. The preferred tool for performing detailed empirical analysis of economic policy is the CGE model. The model is well suited to trade analysis because it can detail structural adjustments within national economies and elucidate their interactions in international markets. The model has been fully documented elsewhere, but a few general comments will facilitate discussion and interpretation of the scenario results that follow (*10*).

Technically, a CGE model is a system of simultaneous equations that simulate price interactions between firms and households in commodity and factor markets. The roles of government, capital markets, and other trading partners are also specified, with varying degrees of detail and passivity, to close the model and account for economywide resource allocation, production, and income determination. The role of markets is to mediate exchange, usually with a flexible system of prices, which are the most important endogenous variables in a typical CGE model. As in a real market economy, commodity and factor price changes induce changes in the level and composition of supply and demand, production and income, and the remaining endogenous variables in the system. In CGE models, an equation system is solved for prices that correspond to equilibrium in markets and satisfy the accounting identities governing economic behavior. If such a system is precisely specified, equilibrium always exists, and a consistent model can be calibrated to a base period data

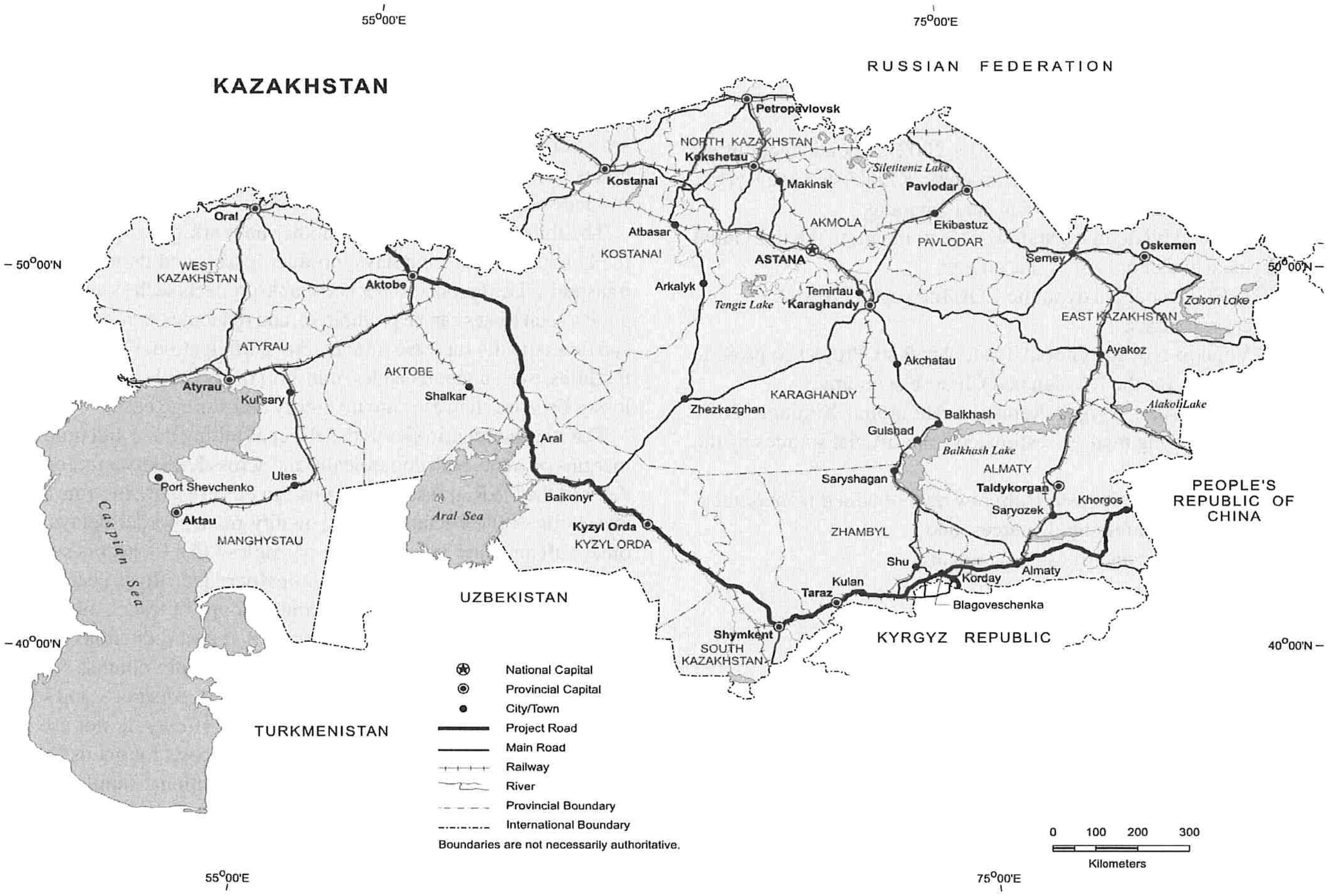

FIGURE 1 Map of road corridor project.

set. The resulting calibrated general equilibrium model can then be used to simulate the economywide (and regional) effects of alternative policies or external events.

The distinguishing feature of a general equilibrium model, applied or theoretical, is its closed-form specification of all activities in the economic system under study. This feature can be contrasted with more traditional partial equilibrium analysis, where linkages to other domestic markets and agents are deliberately excluded from consideration. A large and growing body of evidence suggests that indirect effects (e.g., upstream and downstream production linkages) arising from policy changes are not only substantial but may in some cases even outweigh direct effects. Only a model that consistently specifies economywide interactions can fully assess the implications of economic policies or business strategies. In a multicountry model like the one used in this study, indirect effects include the trade linkages between countries and regions, which themselves can have policy implications. CGE models, supported by reliable data resources, can elucidate these linkages and improve visibility for both policy makers and private stakeholders. Moreover, this kind of simulation framework permits policy makers to identify benefits and costs *ex ante,* recruiting those who gain to support policies and anticipating the adjustment needs of others.

In larger-scale project evaluations such as the one undertaken in this paper, significant economic effects can be seen to spill well beyond the borders of the domestic economy; these effects feed back into the subject economy because of the secondary effects on its trading partners (*11*). To capture these linkages, a multicountry model is more appropriate. This is the framework used in the present analysis, and, as one would expect in a region such as the CAR, with a relatively weak transport infrastructure, the results indicate that spillover effects are very important. The basic structure of a multicountry model consists of the following components:

1. Detailed economic data (2001–2002): social accounting matrices for each of the six CAR economies: Kazakhstan, the Kyrgyz Republic, Mongolia, Russia, China, and Xinjiang;
2. Estimated bilateral trade flow table to integrate the individual country data and detailed fiscal accounts;
3. CA-CGE model: a dynamic CGE forecasting model;
4. Data resources:
   - Version 6 of the Global Trade Analysis Project to provide the core data for the Russian and Chinese economies;
   - Kazakhstan, Kyrgyz Republic, Mongolia, Xinjiang: 2001 social accounting matrices estimated from official sources by the authors;
   - Trade data: estimated from raw data obtained from domestic official and multilateral sources; and
   - Other: trade and transport estimates.

Policy Scenarios

To elucidate the effects of the large-scale infrastructure project discussed here, its properties are examined with incremental policy scenarios, beginning with a baseline and estimating component effects of the project. The policy scenarios include a baseline that considers consensus growth estimates over the scenario period (2008–2030), assuming that no action is taken on the road corridor project. The first alternative policy scenario recognizes only the direct project financial effects and assesses these costs and benefits separately. This analysis includes the Keynesian impact of direct project expenditures and other standard transport project assessment variables, such as vehicle operating cost (VOC) savings and other direct usage benefits of the infrastructure.

These kinds of direct benefits are of course essential to understanding the local returns on infrastructure investments, but they fail to capture the extensive linkage effects across supply and expenditure chains that tie transport infrastructure to the wider universe of economic activity. For example, VOC savings measure the direct cost savings to a vehicle while it is using the corridor, but they do not address the economic implications of actually using the vehicle. For example, a cargo truck may save 10% on transit cost, but these cost benefits will multiply for all the downstream partners of the truck owner, including those who use the truck operator's services, the intermediate and final buyers of its contents, and all upstream and downstream suppliers of goods and services to the operator across its now-expanded range of profitable operation.

As reduced transport cost expands, the physical horizon of profitability for all transport services can be expected to increase the capacity use across a broad spectrum of existing transport–distribution activities, including to stimulate new private investment (*12, 13*). Energy fuel suppliers and appurtenant services (e.g., food and lodging) can be expected to grow not only along the corridor but also across a larger network of trade that has been made profitable by the corridor. This collateral growth effect not only increases road use but also integrates the national and regional economies, increases product variety, and sharpens the comparative advantage of products. Trade and unit profitability are increased by leveraging economies of scale.

The second policy scenario focuses on a central component of these collateral growth effects: the contribution of trade and transport productivity as distribution sectors experience lower costs and pass these gains on to all their client sectors (*14, 15*). The result of this scenario is more transport-intensive growth for the economy at the national, regional, and global levels. Because distribution services are essential to market access, rising productivity in the sector accelerates trade for all other sectors, extending growth in the transport services sector to the rest of the economy.

The third scenario captures another network growth externality: the benefit of reduced delays, product losses, and depreciation on transport-related products. For perishable products such as agricultural goods, such losses can be prohibitive, and reducing them significantly can dramatically increase rural market participation. For other commodities, even nonperishables, transport delays still cause economic losses because they escalate inventory and storage costs.

The fourth scenario shows the effect of falling trade and transport margins on trade, both domestically and across Kazakhstan's borders. Around the CAR, transport margins can be very high, in some cases exceeding 100% because of low-quality roads, border delays, and other soft and hard infrastructure obstacles (*16*). Corridors such as the one being evaluated can dramatically reduce these costs on an average basis, increasing the profitable scope of trade and also its intensity. (It is important to emphasize that cost reductions arising from the project will be averaged across supply chains. Not all operators will experience the same uniform cost reductions, and some operators will have no direct cost reduction if they do not use the corridor. Linkage benefits, via lower invoice costs for goods traveling in the corridor, are still important across national supply chains, however.) The description of the policy scenarios is as follows:

- VOC, including complete project outlays and estimated economic benefits from improved safety, travel time, and reduced vehicle depreciation;

- Productivity, including VOC and estimates of productivity gains for the transport and distribution sectors;
- Losses, including VOC, productivity, and reductions in product losses resulting from spoilage, damage, delays, and other adverse effects of roadway inefficiency; and
- Trade, including VOC, productivity, losses, and estimates of reduced trade and transport cost margins.

Main Results

Key project impact indicators are summarized in Table 1. When all direct and indirect impacts are taken into account (using the all-inclusive Trade scenario), completing the corridor project would lead to a 68% higher real GDP for Kazakhstan by 2020. A decade later (by 2030), these growth benefits would have compounded to achieve a real GDP nearly three times higher than in the baseline scenario. These results are a testament to the massive contribution of infrastructure to economic growth, reaching far beyond the direct financial effects of an individual project.

An important caveat should be kept in mind. Scenario results such as those reported here should be interpreted as indicative of the economy's potential to realize the growth benefits estimated from hypothetical effects on operating costs, productivity, and trade and transport margins. In this sense, these dramatic growth benefits represent upper bounds whose realization may be constrained by institutional imperfections and heterogeneity in the underlying environment (*17*).

For example, in the productivity scenario, a hypothetical change in the productivity of trade and transportation is assumed and is applied in the model uniformly across all users of these services. In reality, the incidence of productivity effects and the degree to which they are conferred upon downstream users will vary across the economy (*18, 19*). This heterogeneity will undermine the full realization of the potential growth benefits. Having said this, experiments with alternative scenarios indicate that the qualitative nature of outcomes is robust and that component policy benefits maintain their relative magnitudes, as does the implied distribution of benefits across stakeholder groups.

TABLE 1 Key Project Impacts, Percentage Change from 2010 Baseline

Impact Indicator	2020	2030
Kazakhstan GDP	68	290
Kazakhstan output		
Transport	79	356
Distribution	77	345
Kazakhstan exports		
Total	32	63
Kazakhstan imports		
Total	33	64
Other CAR	43	152
Russia	4	12
GDP		
PRC	6	17
EU-25	4	11
Other CAR	50	75
Russia	25	54
Kazakhstan exports to		
PRC	36	67
EU-25	28	61
Other CAR	48	75
Russia	27	56
Kazakhstan imports from		
PRC	37	69
EU-25	30	63

Within Kazakhstan, the directly affected transport and trade sectors will be even more dramatically affected, with real output growth being 79% and 77% higher, respectively, by 2020, and more than tripling by 2030. Detailed sector results presented later will show that some activities benefit less than those directly affected by the project but that the economywide effects are still substantial for most sectors.

As would also be expected, foreign trade is stimulated by the project, but less so than domestic economic activity. Exports and imports are 32% and 33% higher, respectively, by 2020, and 63% and 64% higher by 2030. These results are significant, yet they are smaller than domestic GDP growth for several reasons: (*a*) the initial domestic infrastructure is very weak, and the corridor thus makes a bigger contribution to network effects domestically; (*b*) growth over the next 20 years will involve significant emergence of the Kazakhstan internal market and formal sector, reducing the country's very high current trade dependence; and (*c*) GDP growth always includes an important compounding effect of savings–investment accumulation, which is absent from trade linkages.

The GDP effects of the project for Kazakhstan's trading partners reveal significant regional spillover from the project, including, above all, the CAR economies, with a combined GDP that is 43% higher than the baseline in 2020 and 152% higher in 2030. The effect is the greatest for immediate neighbors such as the Kyrgyz Republic, which has high trade shares with and through Kazakhstan and a relatively low initial GDP. This spillover in growth can be expected to radiate across the CAR and beyond and represents an important justification for this project in the regional policy dialogue. Despite their size and diversity, both Russia and China gain significantly from the project through trade linkages, with real GDP gains of 4% and 6%, respectively, by 2020, and 12% and 17% by 2030.

Bilateral trade flows reveal part of the growth leverage process, as CAR economies receive 50% more Kazakhstan exports and send 48% more imports by 2020, with these flows rising 54% and 75%, respectively, by 2030. Bilateral trade with the PRC is the next most dynamic trade flow, with demand for Kazakhstan exports rising 36% and 67% by 2020 and 2030, respectively, and PRC shipments to Kazakhstan growing 37% and 69% more in the same periods. Russian trade with Kazakhstan is about 25% higher in both directions by 2020 and is more than 50% higher by 2030.

More extensive GDP results for the project are given in Figure 2 and Table 2. These results show annual percentage changes in real (2010 U.S. dollars) GDP from the baseline trend, defined as a percent of 2010 GDP. As in Table 1 and as can be expected because of proximity and initial conditions (i.e., relatively low income), the main beneficiaries in relative growth terms are Kazakhstan and its closer regional neighbors.

Given these results, it is important to recognize the stake that all of Kazakhstan's trading partners have in regional infrastructure. European Union countries and even the distant United States capture significant benefits from improved CAR transport infrastructure because of their strong ties to the region through the energy and capital goods markets and their relatively high import and export elasticities. These results support the essential message that the benefits of this large national project are truly multilateral. Significant

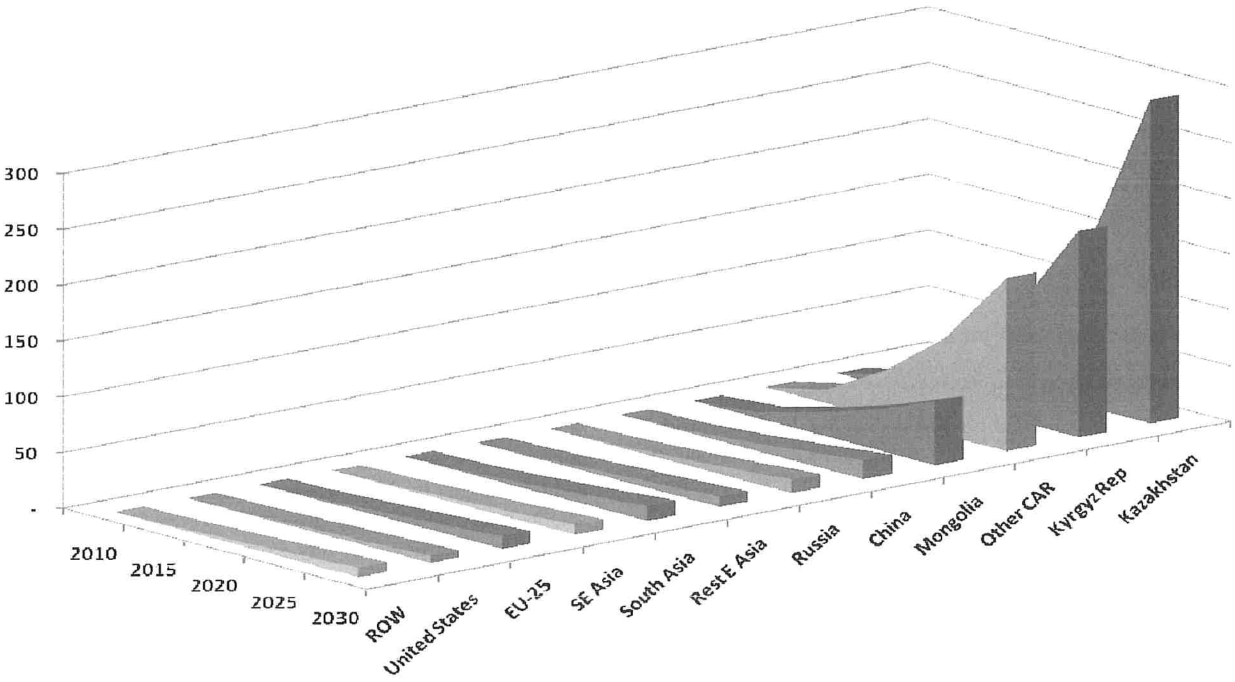

FIGURE 2 Real GDP growth (annual percentage change from 2010 baseline) (ROW = rest of world, EU-25 = European Union countries, SE Asia = Southeast Asia, CAR = Central Asian Republics).

income gains accrue to larger economies, suggesting a broader basis for financing and policy support.

Table 3 shows how real GDP increased by 2030 as a result of the project, separating the total benefit for each economy into each of the four sources of stimulus (i.e., Scenarios 1–4). These results clearly indicate the importance of indirect project effects. Direct or Keynesian effects (isolated in the VOC scenario) are negligible for Kazakhstan's trading partners because this is a national project, yet these partners benefit significantly from linkages of their economies through the corridor.

Even in Kazakhstan, which captures all the Keynesian and other direct project benefits (VOC scenario), the indirect effects are about 10 times greater because the efficiency benefits of improved transport propagate across all market-related activities in the economy. Indeed, higher productivity from transport and distribution services (Prod scenario) make up the largest component of project-induced growth. Although neoclassical effects dominate the growth stimulus, trade and product distribution efficiency are also significant sources of growth advantage.

Given the dominance of indirect effects among infrastructure's contributions to the growth and wider development process, it is reasonable to argue that project finance and assessment are seriously incomplete without accounting for these benefits. The direct project impacts (the Keynesian impacts minus VOC savings) represent less than 1% of the overall gains for the country hosting the project, and none of those (in some cases significant) impacts accrue to neighbors

TABLE 2 Real GDP Growth, Annual Percentage Change from 2010 Baseline

Country	2015	2020	2025	2030
Kazakhstan	17	68	148	290
Kyrgyz Republic	13	50	103	185
Other Central Asian countries	12	44	88	155
Mongolia	5	19	36	57
China	1	6	11	17
Russia	1	4	8	12
Rest of East Asia	1	4	6	9
South Asia	1	5	9	13
Southeast Asia	1	3	6	9
EU-25	1	4	7	11
United States	1	2	4	6
Rest of the world	1	3	6	8

TABLE 3 Average Annual Real GDP Growth Premium in 2030, Percentage Change from 2010 Baseline

Country	VOC	Productivity	Losses	Trade
Kazakhstan	0.61	3.39	2.64	2.19
Kyrgyz Republic	0	3.41	2.09	1.38
Other Central Asian countries	0	2.57	1.68	1.14
Mongolia	0	1.51	1.04	0.06
China	0	0.56	0.34	0.27
Russia	0	0.33	0.21	0.15
Rest of East Asia	0	0.24	0.15	0.11
South Asia	0	0.36	0.29	0.18
Southeast Asia	0	0.29	0.16	0.1
EU-25	0	0.42	0.24	0.19
United States	0	0.15	0.09	0.35
Rest of the world	0	0.40	0.27	0.19

and more distant trade partners. It would be much easier to sustain constructive multilateral dialogue with evidence of this kind, in no small part because investments of this type often lead to unilateral competition for scarce multilateral resources.

While productivity effects represent a significant stimulus to aggregate growth, they are even more important to real output. Cost factors in trade and transport confer profitability and enlarge marketable horizons for intermediaries, which in turn stimulate final and intermediate demands. Productivity growth, however, increases supply elasticities and accelerates the responsiveness of domestic producers to these opportunities. Demand expansion without productivity growth would be significantly dissipated in price escalation, but productivity benefits enable producers to meet rising demand with higher real output.

Figure 3 shows detailed output effects of the project by country and sector. These results are presented in relative terms, as a multiple of baseline values in 2030. As seen with GDP (Table 3), the project has a dramatic effect on Kazakhstan and its immediate neighbors. Because trade and distribution services are such a pervasive cost component across the economy, the effects for the host and proximate economies are relatively uniform. The growth effect is slightly higher in massive, low-value products such as agriculture and heavy industry and is lower in less transport-intensive services.

For more distant economies, the percentage growth effects are understandably smaller, but they are also less uniform. This is because they depend not only on proximity but on induced trade flows and thus patterns of comparative advantage. Thus, benefits to the European Union and United States are larger in the services and food processing sectors but are lower in agriculture and other primary sectors.

When these results are shown in nominal terms, the effects vary more strongly between countries but less so between sectors. Here, it can be seen that both the European Union and the United States receive very large income gains from service linkages to Kazakhstan and all the other parties that experience project-induced growth. This increase is a combined result of linkage through financial services, joint venture management, and other commercial contracting.

Results for Kazakhstan households are consistent with aggregate indicators, but the scenario components contribute in different ways (Table 4). In particular, the trade component is more important to households than to firms because the project improves international market access, both in terms of product variety and prices. Greater import competition also disciplines domestic prices, further enhancing domestic purchasing power.

Table 5 recasts some of the key results (Table 3), focusing on estimated impacts on the target sectors for the project, trade, and transport, including both direct and indirect effects. For comparison, output and trade statistics for the Kazakhstan transport and distribution sectors are presented for the baseline (2010) situation and without the project in 2020.

The following gives 2020 statistic with the project:

- Output: 137,520,
- Exports: 8,857, and
- Imports: 2,546.

The output variable measures the total value of transport and distribution services provided, while imports and exports measure the value of these services provided to and from foreign markets, respectively. For example, without the project, output of the transport and distribution sectors rises from $56,333 million to $76,664 million from 2010 to 2020. With the project, the latter figure nearly doubles, reaching $137,560 million.

All these results are intuitive and consistent with those at the macro level (Table 3), but a few detailed points are of interest. Compared

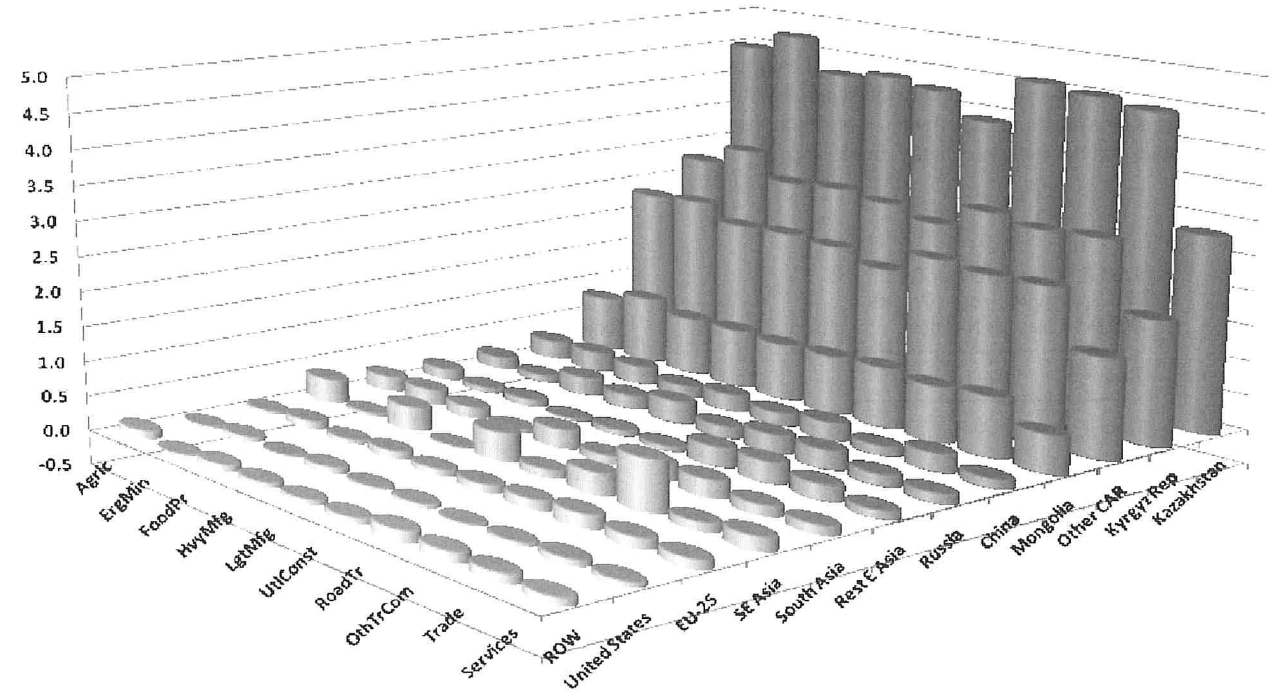

FIGURE 3 Sector output growth in 2030 (percentage change from 2010 baseline) (Agric = agriculture, ErgMin = energy and mining, FoodPr = food processing, HvyMfg = heavy manufacturing, LgtMfg = light manufacturing, UtlConst = utility and construction, RoadTr = road transport, OthTrCom = other transport and communications).

TABLE 4 Real Household Income Growth in 2030, Percentage Change from 2010 Baseline

Country	VOC	Productivity	Losses	Trade
Kazakhstan	0.2	1.74	2.45	3.26
Kyrgyz Republic	0	1.57	1.67	1.64
Other Central Asian countries	0	1.10	1.09	1.01
Mongolia	0	0.59	0.54	0.43
China	0	0.15	0.11	0.08
Russia	0	0.11	0.08	0.05
Rest East Asia	0	0.08	0.06	0.03
South Asia	0	0.10	0.09	0.06
Southeast Asia	0	0.09	0.06	0.03
EU-25	0	0.14	0.09	0.07
United States	0	0.04	0.03	0.10
Rest of the world	0	0.13	0.09	0.06

TABLE 6 Growth Premium 2010 to 2020, Percentage Change in Total Output

Sector	Baseline	Project	Difference
Agriculture	41	156	116
Energy and minerals	38	145	108
Food processing	47	157	110
Heavy manufacturing	41	145	105
Light manufacturing	44	148	104
Utility and construction	49	153	104
Road transportation	42	158	115
Other transport and communications	47	159	112
Trade	46	159	113
Services	49	124	75
Total	44	148	104

with preproject activity, the project adds 61% to total trade and transport activity in the country by 2020, including growth along the corridor and induced trade and transport from feeder road, rail, and other systems. With respect to 2020, the corridor increases national trade and transport activity by 44%.

Also noteworthy is how the project confers comparative advantage on Kazakhstan and, by extension, other export sectors. By 2020, exported trade and transport services have grown 39%, whereas imported trade and transport services have risen only 18%. The difference in competitiveness, reflected in superior investment and growth opportunities for Kazakhstan trade and transport, is reflected in the higher domestic output figure (44%).

Table 6 gives sectoral growth results for the project, indicating that the economywide output would be 104% higher by 2020 but that the individual sectors will benefit to a different extent. The agriculture sector benefits more than average because reduced perishability and increased market access are more important to this sector. Services, being less tradable, still benefit significantly, but less so.

TABLE 5 Kazakhstan Trade and Transport Sector Growth, 2010 Dollars, in Millions

Baseline	2010	2020
Output	53,333	76,664
Exports	3,873	5,429
Imports	1,481	2,076
Change		
Output	84,226	60,895
Exports	4,984	3,427
Imports	1,065	470
Percent		
Output	61	44
Exports	56	39
Imports	42	18

CONCLUSIONS

This report presents results from a multicountry general equilibrium assessment of a large road corridor project in Kazakhstan. The approach is particularly suited to estimating the direct and extensive indirect effects of the project. The results show that the overall benefits of the project far outweigh the project costs. In addition to the positive and significant direct effect of the project, the transboundary spillover confers significant growth leverage to the neighboring and regional economies and can even substantially benefit more distant trading partners.

In comparison, the direct project benefits are relatively small compared to productivity, efficiency, and trade stimulus effects. Productivity gains are the largest source of growth benefits, but reduced losses and trade stimulus are of nearly equal benefit. Trade benefits help the overall economies and extend far beyond the borders of Kazakhstan to large but distant trading partners like the European Union and the United States. Trade margin reductions also increase domestic purchasing power and household real incomes and therefore increase household welfare status (*20, 21*). The project thus positively affects both the overall economy and individual households, suggesting strong support for the project (*22*).

Moreover, as has been demonstrated, estimations of different components of the project's indirect effects are necessary for a comprehensive impact evaluation in general and for sustaining policy dialogue across countries in the region and beyond to improve regional integration, especially in the areas of trade and infrastructure. Application of this type of modeling approach is also desirable for other sectors such as energy and for other cross-border issues and projects.

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Risk Assessment for Transportation of Hazardous Materials Through Tunnels

E. G. Nathanail, S. Zaharis, N. Vagiokas, and P. D. Prevedouros

Two vehicle collisions involving hazardous materials (HM) occurred in 1999 in the tunnels of Mont Blanc between Italy and France and in Tauern, Austria. These collisions showed that the consequences of such crashes are catastrophic for both the motorists in the tunnel and the tunnel itself. This paper presents a methodology to help decision makers estimate the risk associated with the transportation of HM through tunnels and identify remedial measures to minimize unacceptable risk levels. A risk assessment procedure is used to identify the societal risk of the tunnel. If the risk is above an acceptable level, alternative routes are considered, and the overall risk is estimated for both the route with the tunnel and the alternative routes. The route with the minimum risk is established. If the route of minimum risk is through the tunnel, then risk reduction measures are introduced and the risk assessment methodology is implemented to verify the result. The full implementation of the methodology is demonstrated in a case study. The characteristics of the tunnels, the type of HM, and the characteristics of the traffic and accident risk at each tunnel are accounted for. Given an estimate of risk for a tunnel produced by the analytical procedure used in this paper, the applicable regulatory criteria at a given location are found to substantially affect the required response. The response may vary from "no restriction to HM traffic," to "remedies required," to "total restriction of HM type X is advised" for the subject tunnel. The case study considers several remedial actions and assesses their impact on risk and subsequent recommended actions.

This research addresses planning the transportation of hazardous materials (HM) so as to minimize the risk of incidents and the release of HM, taking into account the special requirements of roadway tunnels. The objective is to develop an integrated process for

- Estimation of the risk associated with transportation of HM through tunnels,
- Identification of alternative routes to alleviate the risk generated by tunnels along the route,
- Comparison of risk on alternative routes, and
- Minimization of the risk associated with transportation of HM through tunnels, when other routes are riskier or impractical.

The paper is organized as follows. The existing legal framework for the transportation of HM, internationally and in the European Union (EU), is presented first. The methods and models selected for the assessment of risks are reviewed, and the methodology used and the components, interfaces, and expected outcomes are described.

A case study is then presented to demonstrate the use of the methodology on a freeway with tunnels. The analysis includes individual tunnels, alternative routes, and proposed remedial measures. Conclusions regarding the methodology and its implementation are summarized, and further elaboration of the method and its applicability in the decision-making process of the routing of HM on highways are discussed.

LEGAL FRAMEWORK FOR TRANSPORTATION OF HM

HM are transported daily through many roadway networks, including tunnels. Major accidents involving HM in the tunnels of Mont Blanc, between Italy and France, and Tauern, in Austria, in 1999 showed that although the probability of such events is very low, the consequences can be catastrophic for the motorists in the tunnel and the tunnel itself.

The prohibition of the transportation of HM through tunnels, which typically are part of the trunk network, may cause significant delays, and the rerouting of vehicles with HM onto networks that pass through residential or other environmentally sensitive areas may increase the overall transportation risk.

Road transportation of HM is governed by the international regulations described in the Accord Dangereux Routier (ADR). The agreement was first published in September 30, 1957, by the United Nations (in effect since January 29, 1968) and was first modified in 1975 (in effect since 1985). The 2001 version of the ADR allows the relevant agencies in each country to prescribe additional requirements or restrictions in order to accommodate local needs and objectives (*1*). The most recent revision of the ADR is dated 2009 (*2*). The European Commission accepts and complies with the articles described in the ADR and adopts it in the relevant European Union directives; the member countries codify it in their legislation.

Because of the sensitivity of road tunnels in terms of safety, Paragraph 8.2.2.3.2.n of ADR 2005, a designated section, covers guidelines for driver behavior in tunnels regarding the prevention of accidents and remedial actions that should be taken if an accident occurs (*3*). Before this version was published, in 1999, two major accidents involving the transport of HM through the tunnels occurred. The first was in the Mont Blanc tunnel, where a Belgian transport truck carrying flour and margarine caught fire. The burning margarine load in the trailer spread to other cargo vehicles nearby that also carried combustible loads, resulting in the deaths of 39 people and

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the closure of the tunnel for 3 years (*4*). The other accident occurred in the Tauern tunnel, where a collision followed by a fire was exacerbated by the HM being carried by one of the vehicles involved in the collision. This incident resulted in the deaths of 12 people and the closure of the tunnel for 3 months (*5*). In reaction to these accidents, the European Commission published directive 2004/54/EC, which concerns the minimum safety requirements for tunnels 500-m long or longer that are part of the Transeuropean Roadway Network.

Through the directive, within a time horizon of 6 years (till 2010), member countries were asked to upgrade any tunnels in the above category so that transportation risk would be at an acceptable level. To authorize HM transportation through tunnels, minimum safety requirements should be fulfilled concerning the construction elements, utility networks, signage, surveillance, and emergency response equipment. Also, a risk assessment study should be conducted, the methodology of which, as well as the acceptable risk criteria, are not specified in the directive. The study should be undertaken by an external body and should take into account the geometric and operational characteristics of the tunnels as well as the traffic volume in terms of average daily traffic (ADT) of vehicles transporting HM through tunnels.

RISK ASSESSMENT OF HM TRANSPORTATION

Although extensive research has been done on the estimation of risk associated with the transportation of HM on the roadway network and the comparison of alternative routes in terms of this risk, the rules and regulations that apply to tunnels are generally based on the experience of the responsible authorities rather than on a methodology or process for determining risk. It is estimated that in 62% of the cases in which HM are barred from entering a tunnel, the experience of authorities was the basis of the prohibiting regulation (*6*).

A risk assessment methodology for the estimation of HM through tunnels and along routes that include tunnels was developed by Saccomanno and Haastrup (*7*). Their methodology provides a decision support tool for authorities to objectively lead them to the selection of the most appropriate safety measures for the minimization of the possibility of an accident involving HM, or the minimization of its consequences. Based on the historic data of the probability of an accident and its consequences, various alternative scenarios were tested, assuming safety measures for minimizing accident probability and taking into account the specific conditions that apply in the tunnel. The Monte Carlo method was used for the estimation of the uncertainty as a factor for controlling risk.

Various risk assessment methodologies use statistical analysis, event tree analysis, analytical methods, simulation, subjective modeling, and Bayesian analysis, and all rely on similar fundamentals (*8–12*):

- Identification of the class and volume of the HM;
- Identification of plausible scenarios, which depend on HM properties and quantity;
- Estimation of the probability of the occurrence of an accident involving an HM vehicle and the release of HM; and
- Quantification of the resulting impacts and an estimation of risk to people, property, and the environment.

For the implementation of a risk assessment methodology, extensive historical data concerning highway accidents involving HM and their impacts are required. When adequate databases are not available, risk assessment models may provide good accuracy if applied under the restrictions that were assumed during their development (*13*).

If the methodology allows for a risk index to be estimated for each segment of the trip, the high-risk segments can be identified and alternative itineraries can be selected to minimize the total risk associated with the overall trip (*9, 14*).

Alternative routes may also be selected based on the minimization of one parameter or a set of parameters, such as population at risk, taking into account special population groups such as children, travel time, distance, transportation cost, and vehicle distance on one facility versus another (*11, 15–17*).

Sometimes the parameters considered may be conflicting; for example, the minimization of the population at risk may result in an increase in travel time (*15*). In this case, a function may be used to convert all parameters into cost components, with the optimization aiming at the minimization of total cost (*15*). By implementing different weights for cost components, different optimum routes will likely emerge (*16*). Other techniques may be used, such as multiple objectives optimization, in which more than one objective function is considered; the constrained shortest path technique, in which one objective function minimizes one parameter while the values of other parameters are constrained; and goal programming (*15, 18*).

Bilevel linear programming is used to consider the different priorities of different groups, such as the carriers and the authority responsible for safety. A separate analysis for each group may be designed (*19*). Heuristic methods consider the cost–risk tradeoffs in the objective function (*20*).

The population at risk is the tally of people within a certain distance along the route. Gradient methods in conjunction with Thiessen polygons were used by Abkovitz et al. to allocate population to certain buffer zones (*21*). Lassarre et al. used buffers of a given width around the highway segments to estimate the affected population (based on population density), the number of motorists on the links, and special land uses such as schools (*22*). Factors that are considered in the estimation of the population at risk include accident and release probability and groundwater vulnerability (*16, 17*). Various models have been developed for the estimation of the possibility of HM release at the time of an accident; these are summarized by Schweitzer (*23*).

Minimization of the total risk and equitable allocation of the risk to society have been researched in numerous studies. To identify the optimum route, Carotenuto et al. solved the *k*-shortest path problem, taking into consideration the propagation of the risk to the surrounding area and spreading it equitably in the affected zones of the area (*24*). A similar principle was followed by Bianco et al. through the formulation of a linear bilevel program that is further converted into a mixed-integer linear program or single-level program minimizing the total risk of all origin–destination pairs, solved with integer programming (*25, 26*). Additional relevant work was done by Gopalan et al., Current and Ratick, Akgün et al., and Dell'Olmo et al. (*27–31*).

Bonvicini and Spadoni developed a model in which the individual and societal risk profiles were estimated as a function of the accident probability and the damage effects of the special material(s) transported and then compared to a set of threshold values provided by Dutch criteria, because criteria for Italy were unavailable (*32, 33*). These threshold values were used by other studies (*34*).

PROPOSED METHODOLOGY

Generic Decision Support Framework

Risk assessment is the quantification of the impacts of the transportation of HM along alternative routes. Because release of hazardous substances spreads at a distance from the release source, the estimation of the impact area is required. This refers to the calculation of the radius of impact, in case of accident, along the alternative routes, which depends on the material type and quantity, the scenario associated with the properties of the material, and the prevailing environmental conditions.

The generic decision-making process for the planning of the transportation of hazardous material, taking into account the associated risk, consists of three main functions:

- Identification of alternative routes for the transportation of the vehicles carrying HM,
- Quantification of the impacts associated with the accidents involving HM, and
- Cross-evaluation of the alternative itineraries.

As the literature review showed, various and sometimes contradictory impacts may be estimated:

1. Population impacts are calculated using the number of people who live or work within the affected zone as well as the motorists on the road network that services the transportation of HM.
2. Property damage along the route includes
   - Number of residences,
   - Number of vehicles, and
   - Number of acres by land use.
3. Environmental impacts are estimated for ecologically sensitive areas.
4. A structures index reflects the existence of tunnels and bridges and the way these structures affect risk during transportation of HM. The index is estimated based on the specific characteristics of the bridges and tunnels (e.g., length, type, proximity to other structures).
5. The transporter's cost concerns the cost associated with the transportation of the materials along the alternative routes, including toll fees.
6. Network cost is split into three categories:
   - Construction cost, which concerns the cost associated with the required work that needs to be done in order for an itinerary to be attractive to the transportation of heavy vehicles and HM, as well as the cost of highway engineering, signage, illumination, and equipment;
   - Maintenance cost, which concerns the operators' costs for the maintenance of the pavement and other elements of the roadway (e.g., landscaping); and
   - Toll fees, which include not only tolls but also losses of the operator from the diversion of heavy vehicles transporting HM to longer, slower, nontolled routes.

Decision Support Framework for Transporting HM Through Tunnels

The main assumption of the methodology is that the transportation of HM is initially planned to be accomplished on the main freeway network, which is designed to avoid residential and other sensitive areas. However, the safety level, as prescribed in 2004/54/EC, is endangered by the existence of tunnels, which may increase the risk of a route to unacceptable levels. Because of the complexity introduced with the parallel consideration of all possible impacts from the routing of HM, this methodology is based on the assumption that the index that may quantify the risk is associated with the population. The estimations adopted in the methodology consider the societal risk (SR) index to better represent the effect of a possible HM incident on the population (*13, 32, 34*).

The steps developed in the risk assessment methodology are shown in Figure 1 and briefly discussed below.

Step 1. The risk of the transportation of HM through the tunnel is estimated.

Step 2. The risk index associated with the transportation of HM through the tunnel is compared against threshold values, usually defined by two values, one lower and one higher. When the risk index is below the lower value, then the tunnel is considered safe for the transportation of HM. When the risk index is over the higher value, disallowing the transportation of HM through the tunnel is advised. When the risk index falls between the lower and higher values, then certain measures have to be implemented to reduce the risk index below the lower value.

Step 3. If the risk index of the tunnel is above the lower threshold value, then alternative routes for the transportation of HM have to be identified.

Step 4. Estimation of a risk index associated with the transportation of HM through all the alternative routes is undertaken.

Step 5. If the risk index of transporting HM through the tunnel is above the higher threshold value, then disallowing the transportation of HM through the tunnel is advised, and one of the alternative routes is recommended (the one with the lower overall risk index).

Step 6. If the risk of transporting HM through the tunnel is lower than the higher threshold value, and if there is an alternative route with a lower risk index than the route with the tunnel, the alternative route is recommended for the transportation of HM.

Step 7. If the risk of the best alternative route is higher than the risk of the route with the tunnel (which imposes a high but conditionally acceptable risk, as per the result of Steps 1 and 2), then risk reduction measures are proposed for the tunnel. The risk assessment method is implemented on the tunnel of conditionally acceptable risk in order to identify the measures that will reduce the risk index to an acceptable level.

Estimation of the Risk Index

The quantification of risks is completed with the implementation of four models: the risk source release model, the exposure model, the consequence model, and the risk index model (*13*).

Risk Source Release Model

The risk source release model estimates the probability of an accident involving HM vehicles, the release probability, and the scenario probability regarding the situation that may be created as a result of the accident and the release of HM. The frequency of the involvement of an HM vehicle in an accident is estimated as follows:

$$F_{\mathrm{DG}} = R * x_{\mathrm{DG}} * L * \mathrm{ADT} * 365 \tag{1}$$

where

F_{DG} = frequency of road accidents per year,
R = road accident index for the roadway or tunnel link in accidents per vehicle kilometer,
x_{DG} = proportion of HM vehicles in the overall traffic (as a percentage),
L = length of roadway in kilometers, and
ADT = ADT of the roadway or tunnel link in vehicles per day.

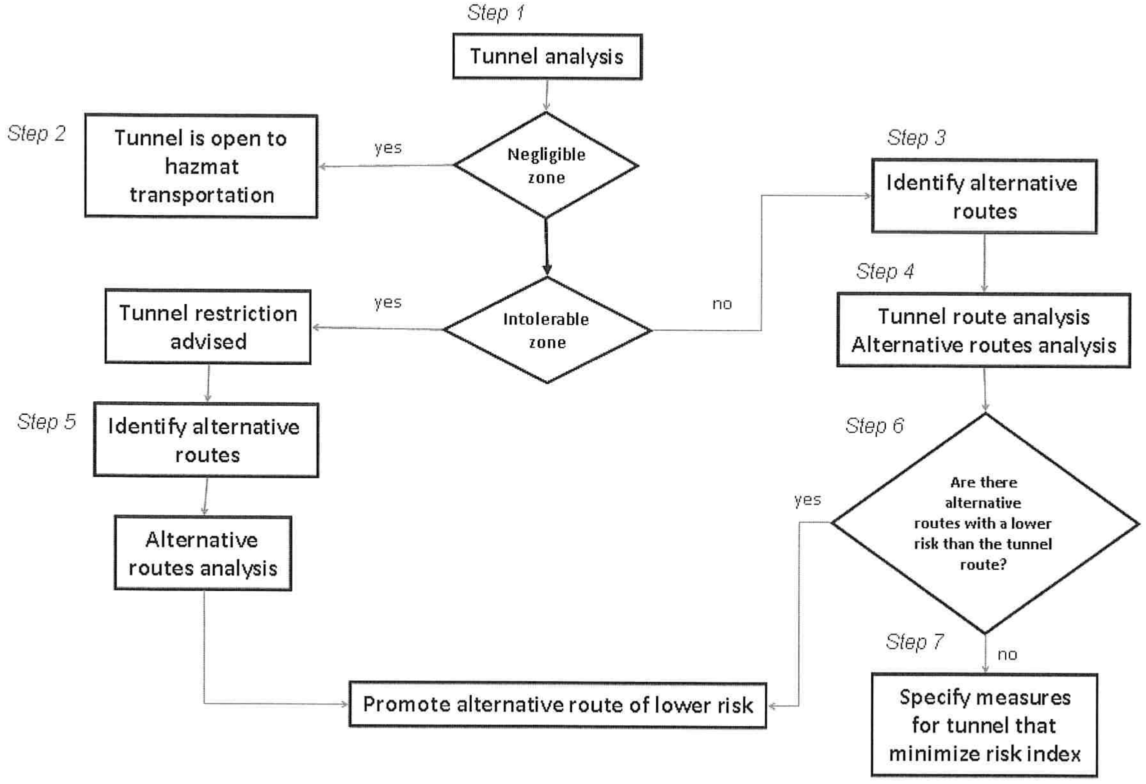

Step 1
Tunnel analysis
Negligible zone
yes
Step 2
Tunnel is open to hazmat transportation
Intolerable zone
yes
Tunnel restriction advised
no
Step 3
Identify alternative routes
Step 4
Tunnel route analysis Alternative routes analysis
Step 5
Identify alternative routes
Alternative routes analysis
Step 6
Are there alternative routes with a lower risk than the tunnel route?
yes
Promote alternative route of lower risk
Step 7
no
Specify measures for tunnel that minimize risk index

FIGURE 1 Decision process framework for HM transportation through tunnels.

According to a study conducted by the Organisation for Economic Co-operation and Development, HM should be grouped into a small number of groups so that the same restrictions apply to the materials belonging to the same category (*35*). In order to identify the groups, the impact scenarios have to be defined first upon the occurrence of an accident and the release of material. These scenarios have been defined as follows:

- Hot boiling liquid expandable vapor explosion (BLEVE). This is a typical situation in which a fireball is created when a container carrying compressed liquefied flammable gas fails and is exposed to fire for some time. The heat makes the liquid boil, the gas vapor expands, the container walls burst and tear, and the flammable gas vapor explodes. The damages are large and widespread. If the incident occurs in a tunnel, then all individuals in it will perish, and the tunnel will likely be destroyed.
- Cold BLEVE (vapor cloud explosion). This scenario is the same as the above, but a fireball is not created. This situation may occur when the container that carries pressurized inflammable gas is exposed to fire. Burst rapture caused by overpressurization may occur, and the consequences will be similar to but milder than those of a hot BLEVE, and consequences will be more concentrated on property damage.
- Flash fire. A flash fire occurs when fuel (typically flammable gas or dust) is mixed with air in concentrations suitable for combustion, which results in a rapidly moving flame front.
- Toxic gas leakage. Such a leak may occur when a container of toxic gas fails and the material is released. Depending on the properties of the material and the prevailing climatologic conditions, this incident may be fatal to the population near the leakage.
- Pool fire. The consequences of the fire vary depending on its size and the way it expands. It may cause injuries, fatalities, and property damages. If the fire occurs in a tunnel, the impacts depend on the geometric characteristics of the tunnel and the traffic volumes.

On the basis of the above scenarios, the World Road Association defined 11 impact categories that are considered as consequences of accidents of HM transportation, along with assumptions for the quantity of release and the leakage size and rate (*36*):

1. Bottled liquid gas BLEVE,
2. Benzene pool fire,
3. Benzene vapor cloud explosion,
4. Chlorine leakage,
5. Containerized liquid gas BLEVE,
6. Containerized liquid gas vapor cloud explosion,
7. Containerized liquid gas fire,
8. Containerized ammonia leakage,
9. Containerized acroleine leakage,
10. Encapsulated (in tubes) acroleine leakage, and
11. Containerized carbon dioxide BLEVE or overpressure burst.

If more than one HM is transported, the overall cargo is categorized under the group with the most stringent restrictions.

Exposure Model

The exposure model estimates the size of the impact area of the 11 scenarios in order to correlate it with the affected population, area, property, and the dose that is released, depending on the distance from the source (*37*). Mathematical models are used for the simulation of each of the above scenarios, with the following indicators at a distance x from the source being estimated:

- Thermal radiation (q'') (pool fire),
- Hyperpressure (po) (vapor cloud explosion, hot BLEVE),
- Smoke temperature (T) (pool fire, vapor cloud explosion, hot BLEVE),
- Carbon monoxide concentration (C), and
- Toxic gases (ammonium, chlorine, akroleine) concentrations (C).

Thermal radiation may be created from a pool fire, a flash fire, or a BLEVE that is the consequence of the explosion of a boiling liquefied expandable vapor (*38, 39*). It is estimated as a function of the burning rate, the burning energy, and the distance from the center of the fire. The widely applied models for the estimation of the hyperpressure, which is caused by the explosion (BLEVE), are based on the model of the trinitrotoluene (TNT) mass equivalent (*39*). The TNT equivalent is used for the estimation of the impacted distance from the event.

The average smoke temperature, which is assumed to be dispersed homogenously in time t and distance x from the center of the fire, takes into account the time required for the heat transfer from the center of the pool fire in distance x, the initial air temperature and other air attributes, as well as the average perimeter of the area (*40*).

The gas concentration at a distance x from the source is estimated on the basis of the amount of the gas that is produced per amount of material burned, the gas mass flow rate, and the relative air and gas molecular weights (*40*).

Consequence Model

The consequence model, as it is implemented in the estimation of the SR index, refers to the exposed population that will be fatally injured, depending on the dose of thermal radiation, hyperpressure, smoke temperature, and concentration of gases.

The most common way of expressing the effect of the thermal radiation to the population (injuries) is through an estimation of the dose of thermal radiation as a function of the thermal radiation, the reaction time, and the escape time (*41, 42*). Dose of thermal radiation, hyperpressure, smoke temperature, and gas concentration are used for the calculation of a probit index correlated to the percentage of fatal injuries, which takes into account the indicative limit values of workers exposure to chemical, physical, and biological agents as established in EU directives 91/322/EU and 96/94/EC (*37*).

The total number of fatal injuries (N) is estimated as follows:

$$N = D_{\text{pop}} * \left[0.95 * A_{90} + 0.70\left(A_{50} - A_{90}\right) + 0.30 * \left(A_{10} - A_{50}\right)\right] \qquad (2)$$

where D_{pop} equals the population density (persons per square meter) and A_y equals the area where the dose results in y% of fatal injuries (in square meters).

For the facilitation of the process, three fatal injury concentration curves have been taken into account, creating three zones. The first zone concerns fatalities from 90% to 100%, the second from 50% to 90%, and the third from 10% to 50%. An average fatal injury rate is assumed for each zone: 95% for the first, 70% for the second, and 30% for the third (*34, 43*). Affected population in tunnels assumes maximum lane occupancy. When traffic diversion or tunnel population mitigation measures are considered, this population is adjusted accordingly.

Risk Index Model

The risk index model estimates the SR index (*42, 44*). The above methodology is implemented for all 11 scenarios, where it applies, and the scenarios, their frequencies, and the associated number of fatal injuries are tabulated in descending or ascending order. The cumulative frequency of the fatal injuries is estimated.

The risk index is then provided through the frequency versus number of fatalities (*F–N*) curve with the results from Equations 1 and 2; that is, the frequency versus the number of fatalities ratio estimates. The route-specific estimate curves are then plotted on the *F–N* diagram and compared against threshold values. Established threshold values are available from the United Kingdom, the Netherlands, and Norway (*33, 45, 46*). These specifications indicate a zone in the diagram called the "as low as reasonably practicable" (ALARP) zone, which is defined by a lower default and a higher *F–N* curve (Figure 2).

Any F/N curve that results from the implementation of a risk assessment method is compared to the ALARP zone. If the curve is below the ALAPR zone (negligible risk), transportation of HM is permitted. If the curve is above the ALAPR zone (tolerance zone), then transportation of HM is prohibited. If part of the *F–N* curve falls within the ALARP zone, then measures have to be taken to reduce the risk index below the ALARP zone before the transportation of HM is advisable.

CASE STUDY OF 15 ATTICA TOLLWAY TUNNELS

The above methodology was applied to the Attica Tollway (locally known as Attiki Odos), an urban freeway in Athens, Greece. Out of the 66.5 km of the freeway, 5.5 km run through 41 tunnels, which vary in length from 48 m to 940 m.

The study focused on the specific restrictions that apply to fuel tankers; they are restricted on three double-tube tunnels in compliance with directive 2004/54/EC. A risk assessment study employing the methodology presented here was conducted with support from the Attica Tollway. The analysis focused on 15 tunnels. The methodology was adapted to the attributes and requirements of the specific roadway and the class of hazardous cargo considered.

The data required for the risk source release model include the accident index of the roadway (a road tanker accident index was not available), the length of each tunnel, its traffic volumes, and the proportion of road tankers in traffic. The accident index was estimated on the basis of the number of accidents and ADT for 2006, resulting in a value of 0.76 accidents per million vehicle-kilometers.

Three cases were considered: pool fire, flash fire, and BLEVE, according to the guidelines of the American Institute of Chemical Engineers (*42*). All cases assumed fuel leakage and creation of a pool. In the case of immediate ignition, a pool fire is created (probability = 0.3906%), and if some compartments of the tanker are affected by the heat, an explosion of the resulting vapors occurs (BLEVE probability = 0.0434%). In the case of delayed ignition, part of the liquid fuel vaporizes, and the delayed ignition of the vapor creates a flash fire (probability = 0.217%). Ignition with small release creates a pool fire (probability = 0.403%). All of the above phenomena create radiation, smoke, and carbon monoxide emissions; BLEVE creates hyperpressure.

On the basis of the above scenarios, the exposure model estimated the doses that the surrounding population would receive, depending on their distance from the source. The consequence model estimated the affected population. The risk index model estimated the F/N curves. Considering the number of fatal injuries per scenario, cumulative frequencies were estimated.

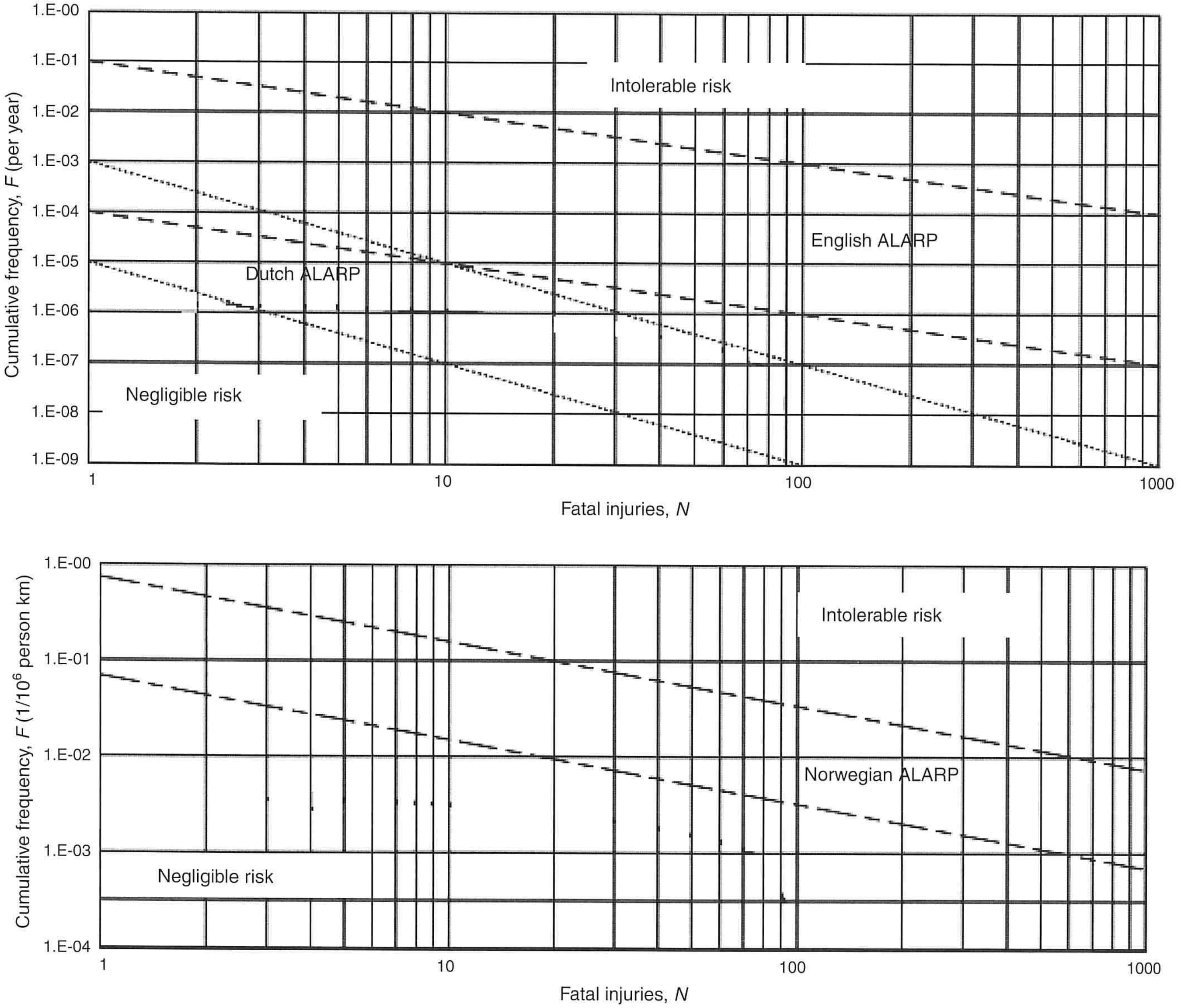


FIGURE 2 U.K., Dutch, and Norwegian specifications for cumulative frequency *F* for *N* or more fatal injuries (*33, 46*).

F/N curves were developed for each of the 15 tunnels studied and compared with the U.K. and Dutch ALARP. When the risk estimate curve of a tunnel was under the ALARP, there was low risk for the transportation of tankers through the tunnel, and no prohibitions were recommended. If the curve was above the ALARP, prohibition of entry was recommended. If the curve fell in the ALARP, alternative routes had to be compared for the risk of routing tankers through them.

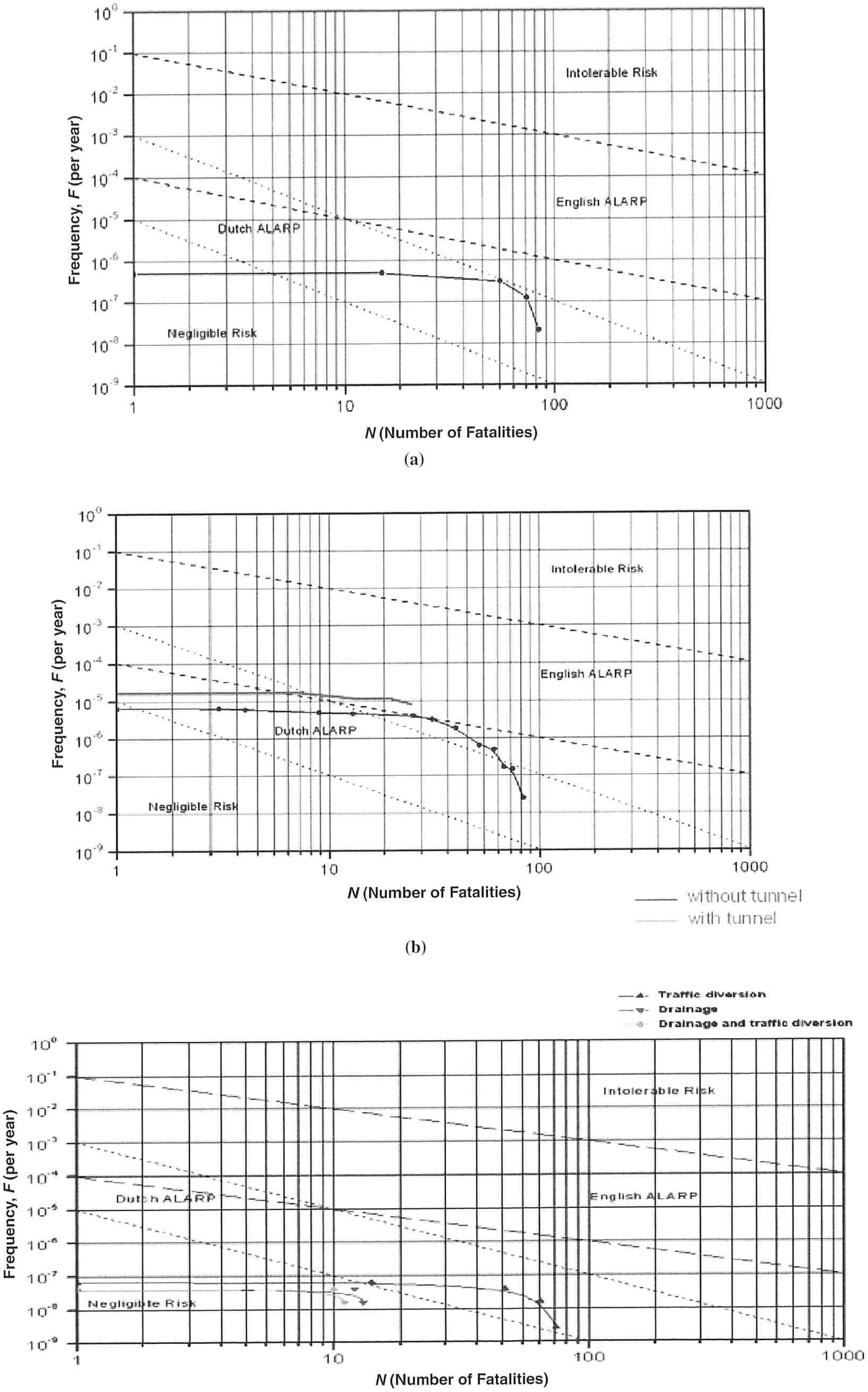
Selected specific results are as follows. When comparing the F/N curves to the U.K. ALARP, there were no tunnels in the intolerable risk area, and two tunnels were in the ALARP zone. When comparing the F/N curves to the more stringent Dutch ALARP,

- Six tunnels were in the negligible risk area,
- Seven tunnels were in the ALARP zone, and
- Two tunnels were in the intolerable risk area.

No measures were necessary for the first six tunnels. Fuel tankers should be restricted in the two tunnels that belong to the intolerable risk area. In fact, these tunnels do restrict fuel tankers, according to the regulations in effect prior to this study. Alternative routings were determined for the seven tunnels in the ALARP zone. Mavri Ora is a representative tunnel, falling in the ALARP zone, and is used to demonstrate the next steps of the methodology (Figure 3*a*). All alternative routes consist of local roads that mainly pass through residential areas. As a result, the F/N curves of the alternative routes had higher risk curves compared with the route on the freeway. However, the maximum number of fatal injuries was lower on the local street alternatives than on the freeway (Figure 3*b*).

Measures were tested to reduce the risk index of the tunnels. The measures stemmed from the safety guidelines provided by directive 54/2004/EC and the specific geometric and technical characteristics of the tunnels. The scenarios for remedial action were as follows:

- Installation of emergency exits (if they did not already exist) to allow people trapped in the tunnel to abandon their vehicles and exit the tunnel;



(a)

(b)

(c)

FIGURE 3 F/N curves for (*a*) tunnel without measures, (*b*) route with the tunnel and the alternative, and (*c*) tunnel with measures.

- Introduction of traffic diversion rules to divert traffic upstream from the tunnel, as needed;
- Installation of a purpose-built drainage system for HM; and
- Combinations of the above.

The findings based on these suggested improvements indicated that in all seven tunnels, the risk index was reduced, and the F/N curve moved into the negligible risk area (Figure 3*c*). For three of these tunnels, transportation of road tankers is currently allowed, whereas the methodology indicated that remedial measures should be taken. For the other four tunnels, transportation of road tankers is prohibited, whereas the methodology indicated that it may be permitted subject to the implementation of the remedial measures that drop the F/N curves under the ALARP zone.

As far as the impact of the individual scenarios on risk, the analysis indicated the following results:

1. Traffic diversion reduces the risk of the tunnel, and the F/N curve drops as compared with the case in which no remedial actions are taken (in Figure 3*a,* the "tunnel without measures"). The frequency and the maximum number of fatal injuries are reduced. However, despite the improvement in tunnel safety compared with the case in which no remedial actions are taken, the F/N curves still lay within the ALARP zone (Figure 3*c*).
2. The installation of the drainage system appears to reduce the risk even more by dropping the F/N curve lower than the traffic diversion measures. This is expected because the HM will be drained before it explodes. The maximum number of fatal injuries is reduced dramatically. With the installation of a designated drainage system, the F/N curves drop below the ALARP zone, which enables the tunnels to accommodate road tankers (Figure 3*c*).
3. The combination of both measures further improves the safety of the tunnels, mainly by reducing the maximum number of fatal accidents. However, reduction in the frequency of the affected population is not observed.

SUMMARY

Road crashes in 1999 involving the transportation of HM through tunnels in Mont Blanc and Tauern caused the deaths of 39 and 12 persons, respectively, and the closure of the Mont Blanc tunnel for 3 years and the Tauern tunnel for 3 months. Although the probability of such events occurring again is low, the consequences can be catastrophic for the motorists in the tunnel and the tunnel itself.

This study developed an integrated analytical process for estimating the risk associated with transportation of HM through tunnels, the identification of alternative routes to alleviate the risk generated by tunnels along the route, and the comparison of risk on alternative routes. When alternative routes are riskier or impractical, then measures to minimize the risk associated with transportation of HM through the route with tunnel(s) were provided.

Implementation of the methodology is demonstrated in a case study. The characteristics of the tunnels, the type of hazardous material, the characteristics of the traffic, and the accident risk at each tunnel were considered. Given an estimate of risk for a tunnel using the analytical procedure in this paper, the applicable regulatory criteria at a given location substantially affect the required response. In the case study considered here, the following results were found.

Risk estimates were compared with the U.K. ALARP. No tunnels were in the intolerable risk area, and two tunnels were in the ALARP zone. The same risk estimates were compared with the Dutch ALARP. Six tunnels were in the negligible risk area, seven were in the ALARP zone, and two were in the intolerable risk area. On the basis of the latter outcome, the study considered several remedial actions and assessed their impact on risk and consequent recommended actions.

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The Transportation of Hazardous Materials Committee peer-reviewed this paper.

Development of Hazardous Materials Shipper Prioritization Application

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In the mid-1990s, an attempt was made to develop a performance-based prioritization program to help the Federal Motor Carrier Safety Administration (FMCSA) during inspection and review of hazardous materials (HM) shippers. During this attempt, it became apparent that there were insufficient performance data to develop such a system (e.g., detailed information on incidents, violations, and shipments). In response, FMCSA developed the HM Package Inspection Program (HMPIP) to focus on inspecting individual shipments of HM at the roadside or on carriers' docks. In response to improvements made over the years to the package inspection data collected during HMPIP inspections, increased HM incident data, and improved departmental data identifying companies involved in shipping HM, FMCSA began a second effort to develop a performance-based HM shipper prioritization program. The Virginia Tech Transportation Institute was asked to review, document, and recommend improvements to the program. A thorough review and examination of the program was performed, and a prioritization software application was developed. Usability testing was performed in five states with existing shipper programs. All results were very good, indicating that the beta version of the program, with minor modifications based on user recommendations, should move forward into a fully functioning application for prioritizing HM shippers within FMCSA.

According to *TRB Special Report 283,* the U.S. Department of Transportation (U.S. DOT) has estimated that approximately 817,300 shipments consisting of 5.4 million tons of hazardous materials (HM) are made daily in the United States, totaling nearly 300 million shipments and 2 billion tons of hazardous materials per year (*1*). On a tonnage basis, this was equivalent to about 18% of the total freight shipped in 1997. Of the 817,300 total daily shipments, approximately 768,900 shipments were carried by truck (94.08%). Since 1997, the amount of freight shipped in the United States has increased by roughly 5%, which suggests that annual HM shipments as of 2005 were on the order of 2.1 billion tons. In order for the Federal Motor Carrier Safety Administration (FMCSA) to inspect and review HM shippers effectively and with currently available resources, it was deemed necessary to develop a performance-based prioritization program to help in the field. Development of the Hazardous Materials Package Inspection Program (HMPIP) began in response to the lack of sufficient performance data available for creating a performance-based prioritization program (e.g., detailed information on incidents, violations, and shipments). The HMPIP is a browser-based software application used during dock and vehicle inspections to record compliance problems with HM packages. This software program can operate as a field system or via a central site. This application populates the database with information that could be used to aid in the prioritization of HM shippers. In response to improvements made over the years to the package inspection data collected during HMPIP inspections, increased HM incident data, and improved departmental data identifying companies involved in shipping HM, FMCSA has begun a second effort to develop a performance-based HM shipper prioritization program.

PURPOSE

The purpose of this study was to review, document, and recommend improvements to FMCSA's HM Shipper Prioritization Program. The Virginia Tech Transportation Institute (VTTI) was tasked with creating a subject-matter expert peer review committee to aid in execution of the project. A thorough review and examination of the current HM Shipper Prioritization Program was performed, which included examining two distinct prioritization algorithms and developing a prioritization software application. This application was then beta tested in five states with existing shipper programs. The focus of these onsite evaluations was usability testing with potential end users. The project methodology, results obtained, and final design of the application are discussed in the sections below.

PEER REVIEW

This project included the development and execution of two peer review meetings, which took the form of a teleconference or webinar. The purpose of the first peer review meeting was to review the study methodology and data collection techniques. The purpose of the second peer review meeting was to present study findings and conclusions. VTTI conducted the first meeting with four subject-matter experts and the second with two subject-matter experts. These subject-matter experts included HM program managers who oversee the inspection and review of shippers for FMCSA. These experts formed the Subject-Matter Expert Committee. Before beginning the recruitment process for the committee, approval from the Virginia Tech Institutional Review Board (IRB) was obtained for all project-related procedures, including human participants. Many

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helpful comments and suggestions were made by the committee members, ranging from potentially useful performance databases to suggested modifications to implement in the final version of the prioritization application.

REVIEW AND EXAMINATION OF PROGRAM

VTTI reviewed the previous work completed by FMCSA on the HM Shipper Prioritization Program and developed a plan of approach to fully implement an HM Shipper Prioritization Application (HMSPA) within FMCSA. This section describes three major examination efforts undertaken by VTTI.

Algorithm Examination

An important first effort undertaken by VTTI was to examine the previously developed algorithms to be used in the prioritization of shippers. Two documents were delivered to VTTI by FMCSA. Each document contained information regarding an algorithm designed for the prioritization of shippers. This section describes the process used by VTTI to examine each algorithm, the results obtained, and the final algorithm used in the project.

Algorithm 1 reported a final shipper priority score. The weighted sum of three types of transportation risk measures—enforcement, inspection, and incident—resulted in the shipper priority score. Therefore, Algorithm 1 can be characterized by Equation 1:

$$\begin{aligned}\text{shipper priority score} = {} & \text{enforcement score} \times \text{inspection score} \\ & \times \text{incident score} \qquad (1)\end{aligned}$$

Algorithm 2 reported a normalized shipper priority score. The weighted sum of three types of transportation risk measures—incidents, enforcement actions, and shipments—was normalized by exposure and resulted in the shipper priority score. Therefore, Algorithm 2 can be characterized by Equation 2:

$$\begin{aligned}\text{shipper priority score} = {} & (\text{incident score} \times \text{incident weighting}) \\ & + (\text{enforcement score} \times \text{enforcement weighting}) \\ & + (\text{shipment score} \times \text{shipment weighting}) \qquad (2)\end{aligned}$$

Although there were several differences between the algorithms, the most notable was the difference between the set of three transportation risk measures used by each algorithm. Also note that although each algorithm contained both Enforcement and Incident measures, each measure was calculated differently within each algorithm. Because Algorithm 1 and Algorithm 2 contained different sets of risk measures, and those measures that appeared to be the same actually were not, comparing the algorithms became a much more difficult task. For these reasons, a decision was made to develop an HM shipper prioritization prototype using a spreadsheet program (Microsoft Excel 2007). This prototype could generate shipper priority scores for each algorithm based on fictional shipper scenarios created by VTTI personnel. Each of four shipper scenarios contained a 12-month inspection, incident, and enforcement history. Each fictional shipper scenario was created with the final shipper priority score in mind. In other words, each shipper scenario had an intended amount of risk associated with it in order to compare the overall priority for each algorithm. For example, of the four shippers (Shippers A, B, C, and D), Shipper B was given scenario attributes that would most likely put it at the highest priority for inspection, whereas Shipper D was given scenario attributes that would most likely put it at the lowest priority for inspection. Shipper A and Shipper C were given scenario attributes that were different from each other; however, each shipper ideally would still be placed somewhere in the middle of a priority list.

Both algorithms had very similar results. As was hypothesized, Shipper B was clearly Priority Number 1, and Shipper D was clearly the lowest priority for both algorithms. The most interesting results were the differences in prioritization of Shipper A and Shipper C between each algorithm. Algorithm 1 ranked Shipper C as a higher priority than Shipper A, and Algorithm 2 ranked Shipper A as a higher priority than Shipper C. Shipper A and Shipper C had very similar prioritization scores. However, results indicated that there were differences between the algorithms that could cause a small shift in the prioritization of shippers.

After closely examining these results, it became apparent that Algorithm 1 recognized the risk of a shipper with a poor safety record (i.e., there was an emphasis on shipper history). The prioritization score was heavily weighted on past inspection and incident violations and enforcement actions. This shows a bias toward consequence risk as it relates to HM shipments. Algorithm 2 placed a significant weight on the exposure of a given shipper. The emphasis was on the number of shipments and what materials were being shipped. The shipment score of Algorithm 2 accounted for almost the entire prioritization score in the aforementioned example. Shippers investigated by the algorithm were the actual headquarters of an operation (usually identified with a shipper DOT number), not a shipper–company branch or location.

Collectively, these results show that both algorithms have great promise. While each has its own structure for calculating priority scores, the end results seem to be very similar based on the examination outlined above. An important factor considered when determining which algorithm to use was the availability of data from the appropriate databases. If, in the future, data are not available for the number of shipments and the associated load descriptions for a shipper of interest, Algorithm 2 would unfairly bias larger shipping companies; that is, it would increase their placement in the prioritization list. Based on this conclusion and the results shown in this report, Algorithm 1 appeared to be the best candidate for incorporation within HMSPA.

Algorithm 1, as previously mentioned, contained three transportation risk measures (enforcement, inspection, and incident). The enforcement score for a given shipper was calculated using four weighted variables: severity, time, multiple enforcements, and material. The inspection score consisted of four similar variables: severity, time, multiple violations, and material. The incident score consisted of four variables: severity, time, multiple incidents, and undeclared shipments.

User Interviews

After the first peer review meeting, participants were given the opportunity to continue their voluntary participation in two follow-up user interviews over the telephone. According to Bauersfeld, a user interview is a one-on-one session between an experimenter and a potential user to discuss the methods currently in place and their expectations of a future application (*2*). Bauersfeld identified three important research steps useful in the development and design of software: (*a*) implement user interviews before design begins, (*b*) implement user interviews and task analysis during the development cycle to evaluate development concepts, and (*c*) implement usability testing at the end of the development cycle to analyze the product's functionality. Steps 1 and 2 were the interviews with the committee members. A different set of five participants were involved in Step 3 during beta testing of this project. The same members that participated in the committee were selected for the user interviews because they already had background knowledge of the project and application. The committee members were interviewed before software development began in order to understand a user's ultimate goals for HMSPA. The goals of this first set of interviews were to establish the expectations and requirements of the system and to investigate the steps that were currently being performed to establish prioritization lists of shippers. The second set of interviews was conducted during the development cycle to obtain feedback on the application interface design. The goal of both user interviews was to obtain information vital to creating a simple and intuitive step-by-step process for the end user.

Overall, the user interviews were extremely successful in establishing the expectations and requirements of the system. For example, participants indicated that some territories were located in incorrect service centers. Participants also had many recommendations for what information field agents would need to see in a table containing prioritization results. The most commonly recorded recommendations consisted of the need for information such as address, city, state, zip code, county, and any DOT numbers available for each HM shipper. Also recommended was the ability to sort this information by column heading. Participants expressed interest in being able to "drill down" to investigate further how priority scores for each shipper were calculated. A final recommendation was made in regard to distinguishing between a pure shipper and a shipper–carrier. According to participants, a pure shipper is an entity that offers HM only for transportation and must recruit a motor carrier to pick up and deliver the product. A shipper–carrier is an entity that manufactures and distributes some or all of its own products. The company has opted to own its own trucks and deliver products itself, usually consisting of home heating oil, propane, kerosene, and the like. Participants indicated that if possible, it would be helpful to make this distinction in the results table. VTTI did not implement this distinction before beta testing and could not find the location within the databases that contained this distinction. As previously mentioned, shippers investigated by the algorithm are the actual headquarters of an operation, not a shipper, shipper–company branch, or location.

Development of HMSPA

VTTI began developing the foundation and structure of the web-based application early in the project. VTTI exercised established human factors principles during the design and development of this application in combination with feedback obtained during user interviews with committee members. The development of the beta version of HMSPA had the goal of creating three web pages: the Home Page, Prioritization Page, and Results Page. The beta version of HMSPA was not an online, web-based application. It was offline and used locally housed data. The Home Page was created with a login area to the left and a feedback box to the right for users to supply comments and recommendations. The main content of the Home Page consisted of a brief description of the site and the databases used for the calculation of priority scores for shippers. The purpose of the Prioritization Page was for a user to choose the geographic area to prioritize shippers by using a map to click service center areas or by selecting each individual state of interest near the bottom. Finally, an interactive Results Page was created to display the prioritized list of shippers generated from the Prioritization Page. The results table contained eight different columns of information, and the user can sort data by column. The columns were as follows: priority score, company name, address, city, state, zip code, phone, and DOT number.

The source of prioritization for HMSPA was an algorithm designed to evaluate the potential risk for an HM shipper. The algorithm used a shipper's historical information to extrapolate future risk characteristics. The algorithm required the combination of various data extracted from several databases for the same shipper and thus required a way to uniquely identify each shipper across databases. For HMSPA to successfully use this algorithm, VTTI had to organize the data in one central location for access. The following databases were selected as data sources based on discussion between FMCSA and VTTI personnel: HMPIP, the Motor Carrier Management Information System (MCMIS), the Enforcement Management Information System (EMIS), and the Hazardous Materials Incident Report System (HMIRS). The first three were databases controlled by FMCSA. The last database was controlled by the Pipeline and Hazardous Materials Safety Administration (PHMSA). FMCSA and PHMSA were unable to grant VTTI direct access to these databases. Instead, VTTI was provided static exports of the HMPIP and the MCMIS data, as well as a Microsoft Excel spreadsheet containing the results of a query against the EMIS database. Data from HMIRS was retrieved from the PHMSA Incident Reports Database Search web page on August 1, 2008, in comma-separated value files (*3*).

The algorithm required the use of varying severity levels to calculate individual scores for a given shipper. These severity levels were based on Code of Federal Regulations (CFR) section numbers. Although most of the databases contained the CFR section numbers cited for a violation or enforcement action, they did not provide a level of severity. This was provided by FMCSA in hardcopy form. After collecting all of the necessary data sources, VTTI began the process of creating locally housed databases for use in the creation of the beta version of HMSPA. The HMPIP data export and MCMIS data export were directly imported as local databases. The HMIRS data, EMIS data, and severity-level data were each imported as a single table. The HMIRS and EMIS data became single-table databases. The severity-level data were imported into the HMPIP database as an additional table.

Attributing the correct scores to a proper shipper was essential in creating an accurate prioritization score. Thus, as each score was calculated, it was assigned a unique identifier. It became clear when filtering and evaluating the data that the shipper name alone was insufficient to create this unique identity. The most frequent issue with shipper names was misspellings. This would cause the score associated with the misspelled shipper to be counted separately from the rest of the shipper's score. To prevent this from happening, VTTI created a unique identifier that allowed cross-database querying for a given shipper. To accomplish this, VTTI used a technique called Soundex. Developed by Robert C. Russell, Soundex is a phonetic index created to match misspelled surnames (*4*). The principle behind Soundex is that the English language has certain letters easily confused with other letters or combinations of letters. The Soundex technique allowed similar names to be matched up with one another, even if placed far apart in a large listing. This technique was improved upon with the development of the American Soundex System. VTTI used the American Soundex System to abbreviate the shipper name and the shipper city. The abbreviations were then concatenated, and the two-digit state code was added to create a unique identifier.

For example, a fictional shipper by the name of VTTI in Blacksburg, Virginia, would have the unique identifier of

VTTI = V300
Blacksburg = B421
Therefore, V300 + B421 + VA = V300B421VA

A reliability test was performed by running the unique identifier creation query on all shippers in the locally housed HMIRS database. After creating the unique identifier, a random selection of 15% was chosen for manual verification. Manual verification consisted of checking both the shipper name for consistency and the unique identifier for accuracy. VTTI found that the unique identifier technique proved successful 98.84% of the time with a 95% Wald confidence interval of 98.35%, 99.33% (*5*). The confidence interval was calculated using Equation 3:

$$\text{confidence interval} = \hat{\pi} \pm Z_{\alpha/2}\sqrt{\frac{\hat{\pi}(1-\hat{\pi})}{n}} \tag{3}$$

where

$\hat{\pi}$ = sample proportion,
$Z_{\alpha/2}$ = z-value with an area of $\alpha/2$ to its right and left (obtained from a table), and
n = sample size.

On the basis of these results, VTTI used this technique to create unique identifiers for each shipper in the three databases (HMIRS, HMPIP, and EMIS) to accurately combine individual scores. The prioritization of shippers used an algorithm developed by ABSC Consulting and modified by VTTI. There were three distinct categories of shipper performance evaluated: enforcements, inspections, and incidents. The overall goal was to use the information specific to a given shipper to determine the likelihood of a violation or incident in the future. Those shippers with the calculated highest risk of future incident were assigned the highest priority, and those with the lowest risk were assigned the lowest priority. Thus, the Prioritization Score (PS) was calculated as the sum of each individual score, as shown in Equation 4:

$$\text{prioritization score} = ES + I_N S + I_T S \tag{4}$$

where

ES = enforcement score,
$I_N S$ = inspection score, and
$I_T S$ = incident score.

The enforcement score largely used the EMIS database as its data source, the inspection score used the HMPIP, and the incident score used the HMIRS.

BETA TESTING

The purpose of this task was to beta test and implement HMSPA in states with an existing shipper program. This allowed an opportunity to correct or enhance features based on user input. The focus of these on-site tests was usability testing with potential end users. Both subjective and objective data were collected by way of questionnaires, performance tasks, and audio recordings of the sessions.

Participants

VTTI performed these usability tests with five participants in five states with an existing shipper program. Approval for participant experimentation for this project was approved by the Virginia Tech IRB Human Assurances Committee. All participants signed informed consent forms prior to involvement. The age of participants ranged between 39 and 49 years (mean of 45.8). The range of job experience for participants was between 4 and 22 years (mean of 12). Gender was not considered in the selection of the participants. In the end, only male participants volunteered.

Apparatus

All usability testing was performed on a Dell Latitude D630 laptop computer with an optical mouse. The screen resolution was set to 1140 by 900 pixels, and the color quality was set at the highest level (32 bit). The dots-per-inch (DPI) setting was normal at 96 DPI. The laptop was positioned on a desk or table, depending on the testing environment for each individual site. HMSPA was displayed on the laptop, and usability testing software developed by Morae (Version 3.0) was utilized for recording audio and the time spent on the task.

Procedure

The VTTI experimenter visited Boise, Idaho; Minneapolis, Minnesota; Richmond, Virginia; Sioux Falls, South Dakota; and Valdosta, Georgia. At each site, procedures involving participants were executed identically, with the exception of environmental differences such as the room or office in which the testing occurred or the desk or table on which the laptop was positioned. Each participant was tested in one session lasting less than 1 h. At the beginning of the study, the participant was greeted and asked to read and sign the informed consent form. A short project introduction was given by the experimenter, and any participant questions were answered. The participants were then instructed to familiarize themselves with the Home Page until they were ready to begin performing prioritization tasks. Three prioritization tasks were performed by each participant. Each task began on the Prioritization Page. Participants were instructed to take as long as needed and not to worry about making any mistakes. Participants were also instructed to perform each task without experimenter input or guidance and were assured that after the task had been completed, an opportunity to share any comments would be available. All mouse movements, button clicks, and audio were recorded in order to calculate task time and any mistakes made, as well as to capture any comments made by each participant.

The objective of each task was for each participant to use the Prioritization Page to create a prioritization list of shippers for a set geographical region. The geographical region for the first task was the state of Florida. The geographical region for the second task was the Eastern Service Center. The geographical region for the final task was the entire United States. After each task was finished, a post-task questionnaire consisting of one rating scale was given to each participant, and any necessary follow-up questions were asked.

Upon successful completion of each task, the Results Page, which consisted of an interactive table, was displayed. The experimenter briefly described the contents of the table and its interactive capabilities. After all tasks were completed, final post-task interviews and exit questionnaires were performed consisting of open-ended questions and additional rating scales.

RESULTS

In general, the purpose of the usability testing was to evaluate HMSPA by collecting both objective and subjective data to correct or enhance features before implementation within FMCSA. The results section of this report will first provide descriptive statistics about the participants and the tasks performed. Next, results from the rating scales will be discussed. Finally, a sample of comments received from participants will be presented.

Participant and Task Descriptive Statistics

As previously mentioned, the age of participants ranged between 39 and 49 years (mean of 45.8). The range of job experience for participants was between 4 and 22 years (mean of 12). Gender was not considered in selection of the participants. In the end, only male participants volunteered. Each participant successfully completed every task, resulting in a 100% successful task completion rate. Each testing session ranged between 33 and 45 min [mean = 38.40, standard deviation (SD) = 4.67]. The mean time for the familiarization period and each individual performance task is shown in Figure 1. The familiarization period for the Home Page ranged between 55.40 and 221.09 s (mean = 104.20, SD = 70.65). The task of prioritizing a list of shippers by state ranged between 28.40 and 70.56 s (mean = 41.63, SD = 18.01). The task of prioritizing a list of shippers by service center ranged between 9.21 and 57.65 s (mean = 22.38, SD = 20.00). The task of prioritizing a list of shippers for the entire United States ranged between 12.60 and 25.82 s (mean = 17.33, SD = 5.00). On the basis of these results, without experimenter instruction on how to perform these prioritization tasks using HMSPA, it is possible for users to visit the site for the first time, familiarize themselves with it, and perform a prioritization task in less than 5 min.

Ratings

After each task, a rating scale was administered to each participant to judge the level of difficulty involved. Rating scales were intended to provide information on multiple parameters:

- Difficulty (tasks individually and overall),
- Usefulness,
- Satisfaction,
- Reaction,
- Arrangement,
- Terminology,
- Ability to learn, and
- Correcting mistakes.

For analysis purposes, the rating scale responses were converted to numerical values. Each scale had nine vertical delineators. They were numbered from 1 on the left (extremely difficult) to 9 on the right (extremely easy). The middle of the scale was then numbered as a 5. A value of 5 would ordinarily correspond to a "moderate" or "neutral" rating. Values greater than 5 would correspond to favorable ratings, and values smaller than 5 would correspond to unfavorable ratings. The mean difficulty rating for each performance task is shown in Figure 2. The task of prioritizing a list of shippers by state ranged between a rating of 7 and 9 (mean = 8.4, SD = 0.9). The task of prioritizing a list of shippers by service center ranged between a rating of 8 and 9 (mean = 8.8, SD = 0.4). The task of prioritizing a list of shippers for the entire United States ranged between a rating of 8 and 9 (mean = 8.8, SD = 0.4). On the basis of these results, researchers can conclude that all tasks were rated very high, indicating that the tasks were very easy to perform.

Other rating scales were administered after the tasks were completed during the post-task interview and exit questionnaire. The mean rating for each parameter is shown in Figure 3. On the basis of these results, researchers can conclude that all parameters were rated very high, indicating that the tasks were very easy to perform.

The mean rating value of 7.2 for the difficulty of correcting a mistake is misleading. At first glance, it may appear that the task of correcting a mistake was more difficult than other parameters. The question presented for this parameter was, "What was your overall impression regarding the ability to correct your mistakes?" The mean

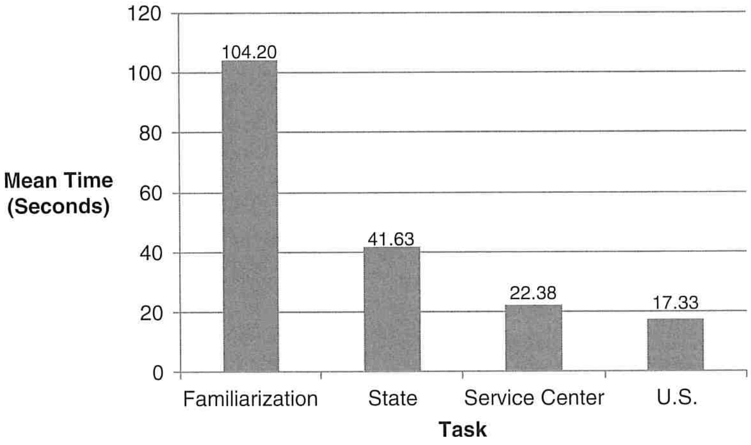
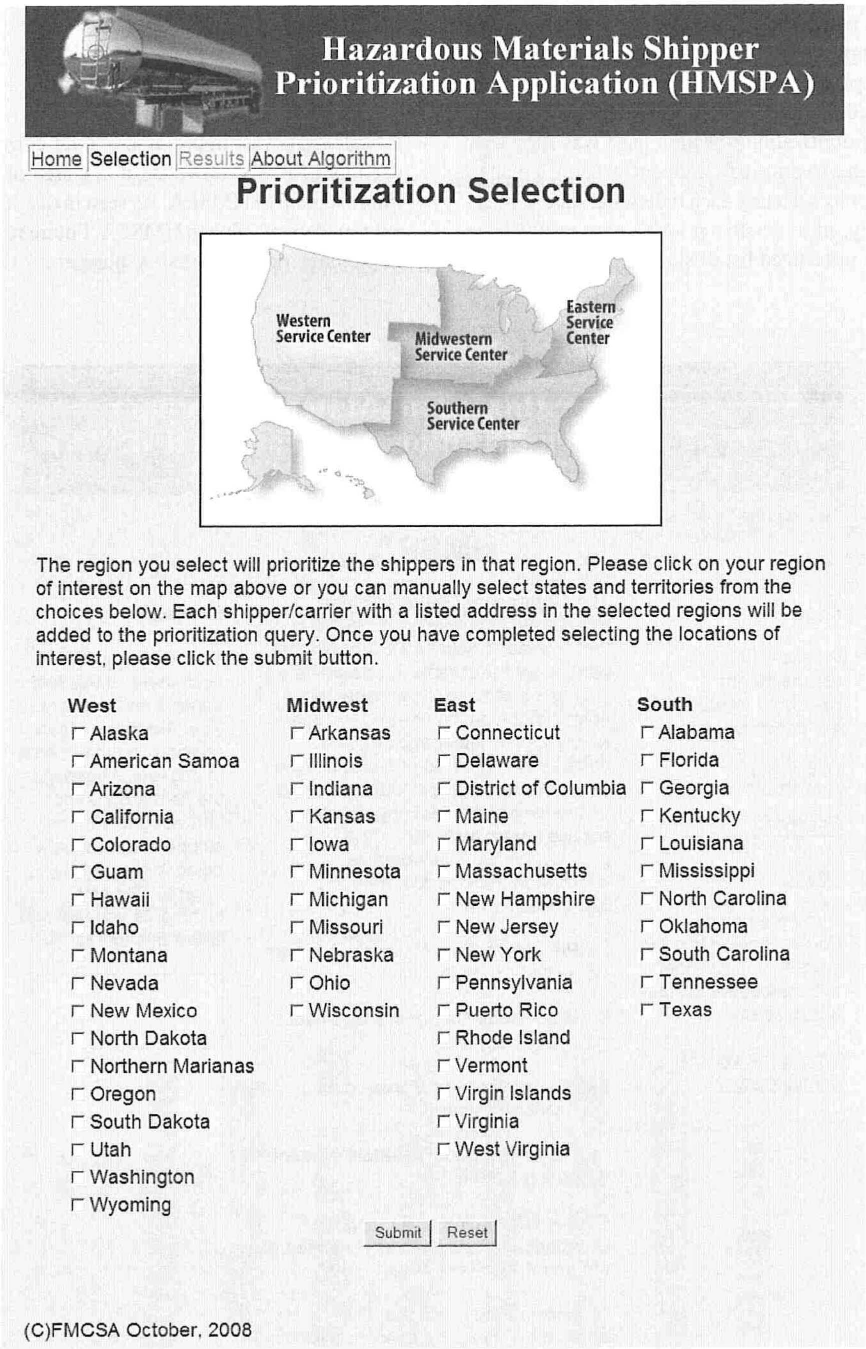


FIGURE 1 Plot of mean time as function of task.



Hazardous Materials Shipper Prioritization Application (HMSPA)

Prioritization Selection

The region you select will prioritize the shippers in that region. Please click on your region of interest on the map above or you can manually select states and territories from the choices below. Each shipper/carrier with a listed address in the selected regions will be added to the prioritization query. Once you have completed selecting the locations of interest, please click the submit button.

West

☐ Alaska
☐ American Samoa
☐ Arizona
☐ California
☐ Colorado
☐ Guam
☐ Hawaii
☐ Idaho
☐ Montana
☐ Nevada
☐ New Mexico
☐ North Dakota
☐ Northern Marianas
☐ Oregon
☐ South Dakota
☐ Utah
☐ Washington
☐ Wyoming

Midwest

☐ Arkansas
☐ Illinois
☐ Indiana
☐ Kansas
☐ Iowa
☐ Minnesota
☐ Michigan
☐ Missouri
☐ Nebraska
☐ Ohio
☐ Wisconsin

East

☐ Connecticut
☐ Delaware
☐ District of Columbia
☐ Maine
☐ Maryland
☐ Massachusetts
☐ New Hampshire
☐ New Jersey
☐ New York
☐ Pennsylvania
☐ Puerto Rico
☐ Rhode Island
☐ Vermont
☐ Virgin Islands
☐ Virginia
☐ West Virginia

South

☐ Alabama
☐ Florida
☐ Georgia
☐ Kentucky
☐ Louisiana
☐ Mississippi
☐ North Carolina
☐ Oklahoma
☐ South Carolina
☐ Tennessee
☐ Texas

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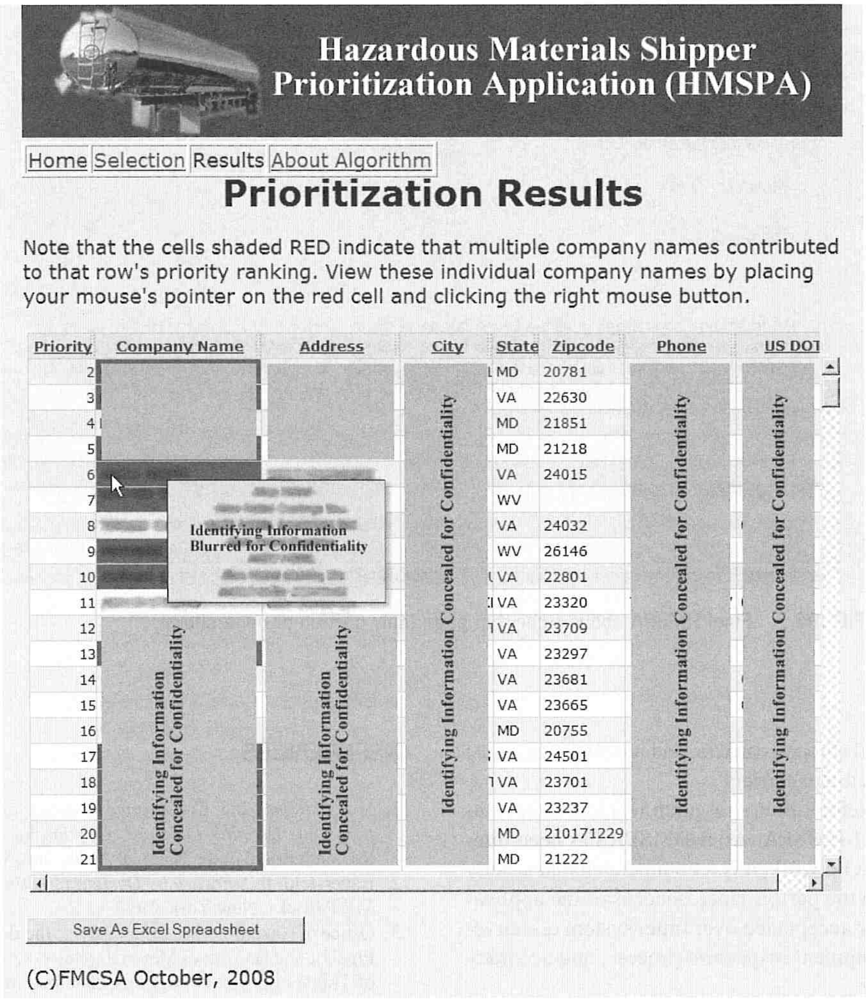
FIGURE 5 Final HMSPA prioritization selection page.



Hazardous Materials Shipper
Prioritization Application (HMSPA)
Home
Selection
Results
About Algorithm
Save As Excel Spreadsheet

Prioritization Results

Note that the cells shaded RED indicate that multiple company names contributed to that row's priority ranking. View these individual company names by placing your mouse's pointer on the red cell and clicking the right mouse button.

Priority	Company Name	Address	City	State	Zipcode	Phone	US DOT
2	[redacted]	[redacted]	Identifying Information Concealed for Confidentiality	MD	20781	Identifying Information Concealed for Confidentiality	Identifying Information Concealed for Confidentiality
3	[redacted]	[redacted]		VA	22630		
4	[redacted]	[redacted]		MD	21851		
5	[redacted]	[redacted]		MD	21218		
6	[redacted]	[redacted]		VA	24015		
7	[redacted]	[redacted]		WV			
8	[redacted]	[redacted]		VA	24032		
9	[redacted]	[redacted]		WV	26146		
10	[redacted]	[redacted]		VA	22801		
11	[redacted]	[redacted]		VA	23320		
12	Identifying Information Concealed for Confidentiality	Identifying Information Concealed for Confidentiality		VA	23709		
13				VA	23297		
14				VA	23681		
15				VA	23665		
16				MD	20755		
17				VA	24501		
18				VA	23701		
19				VA	23237		
20				MD	210171229		
21				MD	21222		

Identifying Information Blurred for Confidentiality

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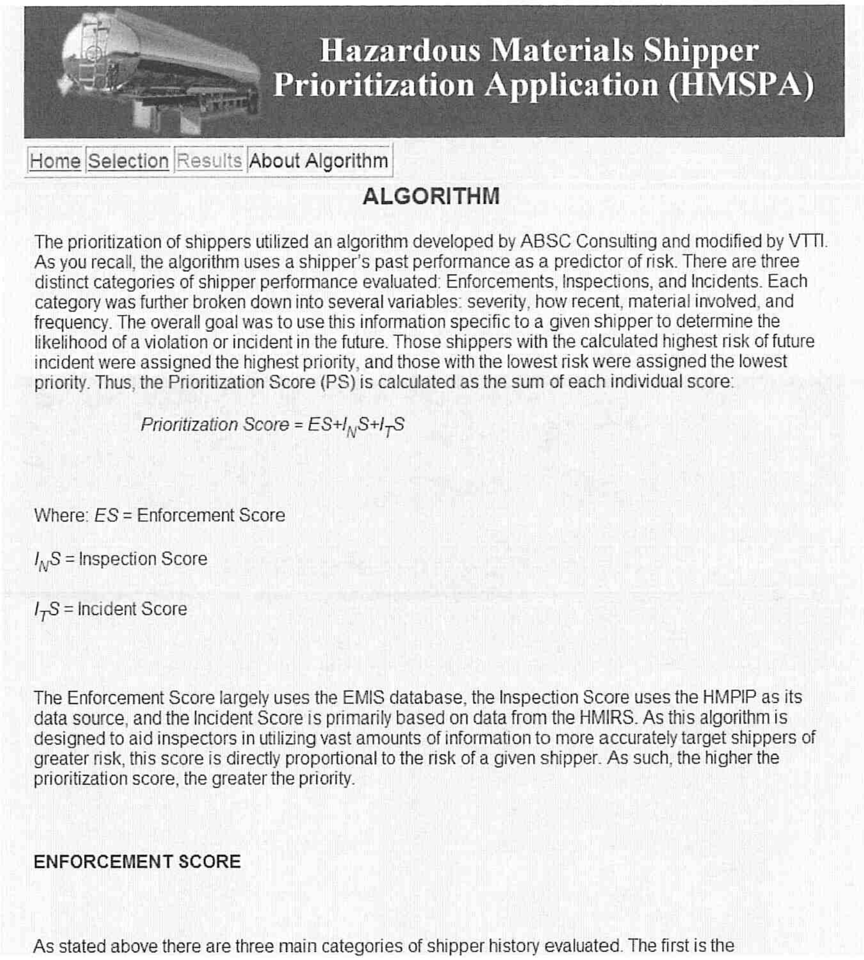
FIGURE 6 Final HMSPA prioritization results page.


Hazardous Materials Shipper Prioritization Application (HMSPA)
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ALGORITHM

The prioritization of shippers utilized an algorithm developed by ABSC Consulting and modified by VTTI. As you recall, the algorithm uses a shipper's past performance as a predictor of risk. There are three distinct categories of shipper performance evaluated: Enforcements, Inspections, and Incidents. Each category was further broken down into several variables: severity, how recent, material involved, and frequency. The overall goal was to use this information specific to a given shipper to determine the likelihood of a violation or incident in the future. Those shippers with the calculated highest risk of future incident were assigned the highest priority, and those with the lowest risk were assigned the lowest priority. Thus, the Prioritization Score (PS) is calculated as the sum of each individual score:

$$\textit{Prioritization Score} = ES+I_NS+I_TS$$

Where: ES = Enforcement Score

I_NS = Inspection Score

I_TS = Incident Score

The Enforcement Score largely uses the EMIS database, the Inspection Score uses the HMPIP as its data source, and the Incident Score is primarily based on data from the HMIRS. As this algorithm is designed to aid inspectors in utilizing vast amounts of information to more accurately target shippers of greater risk, this score is directly proportional to the risk of a given shipper. As such, the higher the prioritization score, the greater the priority.

ENFORCEMENT SCORE

As stated above there are three main categories of shipper history evaluated. The first is the

FIGURE 7 Final HMSPA about algorithm page (only portion of page shown).

between pure shippers and shipper–carriers, and the ability to adjust the algorithm for use with motor carriers.

The second area of potential future research would be to evaluate the implementation of HMSPA. After HMSPA has been integrated within the FMCSA network, it is recommended that a study be conducted to evaluate the performance benefits of the application in the field (i.e., user acceptance over time, system effectiveness in improving the shipment inspection process, and accuracy of the current algorithm).

ACKNOWLEDGMENTS

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The Transportation of Hazardous Materials Committee peer-reviewed this paper.

TRANSPORTATION RESEARCH RECORD: JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Peer Review Process

The *Transportation Research Record: Journal of the Transportation Research Board* publishes approximately 25% of the more than 3,000 papers that are peer reviewed each year. The mission of the Transportation Research Board (TRB) is to disseminate research results to the transportation community. The Record series contains applied and theoretical research results as well as papers on research implementation.

The TRB peer review process for the publication of papers allows a minimum of 30 days for initial review and 60 days for rereview, to ensure that only the highest-quality papers are published. At least three reviews must support a committee's recommendation for publication. The process also allows for scholarly discussion of any paper scheduled for publication, along with an author-prepared closure.

The basic elements of the rigorous peer review of papers submitted to TRB for publication are described below.

Paper Submittal: June 1–August 1

Papers may be submitted to TRB at any time. However, most authors use the TRB web-based electronic submission process available between June 1 and August 1, for publication in the following year's Record series.

Initial Review: August 15–November 15

TRB staff assigns each paper by technical content to a committee that administers the peer review. The committee chair assigns at least three knowledgeable reviewers to each paper. The initial review is completed by mid-September.

By October 1, committee chairs make a preliminary recommendation, placing each paper in one of the following categories:

1. Publish as submitted or with minor revisions,
2. Publish pending author changes and rereview, or
3. Reject for publication.

By late October, TRB communicates the results of the initial review to the corresponding author indicated on the paper submission form. Corresponding authors communicate the information to coauthors. Authors of papers in Category 2 (above) must submit a revised version addressing all reviewer comments and must include a cover letter explaining how the concerns have been addressed.

Rereview: November 20–January 25

The committee chair reviews revised papers in Category 1 (above) to ensure that the changes are made and sends the Category 2 revised papers to the initial reviewers for rereview. After rereview, the chairs make the final recommendation on papers in Categories 1 and 2. If the paper has been revised to the committee's satisfaction, the chair will recommend publication. The chair communicates the results of the rereview to the authors.

Discussions and Closures: February 1–May 15

Discussions may be submitted for papers that will be published. TRB policy is to publish the paper, the discussion, and the author's closure in the same Record.

Many papers considered for publication in the *Transportation Research Record* are also considered for presentation at TRB meetings. Individuals interested in submitting a discussion of any paper presented at a TRB meeting must notify TRB no later than February 1. If the paper has been recommended for publication in the *Transportation Research Record*, the discussion must be submitted to TRB no later than April 15. A copy of this communication is sent to the author and the committee chair.

The committee chair reviews the discussion for appropriateness and asks the author to prepare a closure to be submitted to TRB by May 15. The committee chair reviews the closure for appropriateness. After the committee chair approves both discussion and closure, the paper, the discussion, and the closure are included for publication together in the same Record.

Final Manuscript Submittal: March 15

In early February, TRB requests a final manuscript for publication—to be submitted by March 15—or informs the author that the paper has not been accepted for publication. All accepted papers are published by December 31.

Paper Awards: April to January

The TRB Executive Committee has authorized annual awards sponsored by Groups in the Technical Activities Division for outstanding published papers:

- Charley V. Wootan Award (Policy and Organization Group);
- Pyke Johnson Award (Planning and Environment Group);
- K. B. Woods Award (Design and Construction Group);
- Patricia F. Waller Award (Safety and System Users Group);
- D. Grant Mickle Award (Operations and Preservation Group); and
- John C. Vance Award (Legal Resources Group).

Other Groups also may nominate published papers for any of the awards above. In addition, each Group may present a Fred Burggraf Award to authors 35 years of age or younger.

Peer reviewers are asked to identify papers worthy of award consideration. Each Group reviews all papers nominated for awards and makes a recommendation to TRB by September 1. TRB notifies winners of the awards, which are presented at the following TRB Annual Meeting.

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